Design, characterization and reliability studies of passive aligned optical modules

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Design, Characterization, and Reliability Studies of Passive Aligned Optical Modules

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Abstract

Optical communication is one of the most promising areas of research in the field of micro & optoelectronics, largely due to the ever-increasing demand for bandwidth. Cost effective solutions and reliability of the optical devices are the key challenges in adopting the optical framework on the local area network (LAN). Since optical ICs are not fully developed, assembly of different optical components on a common platform is the only viable solution. Passive alignment technology and polymer materials are emerging as cost effective solutions for optical modules. This research thesis deals with the assembly of single mode optical transceiver modules using polymeric materials employing the passive alignment methodology and investigating its reliability. The objective of this research was to develop methodologies to characterize, simulate, and predict the effect of packaging design, material properties, and thermo-mechanical induced stresses on the optical coupling efficiency of the transceiver module.

A passively aligned optical sub-assembly (OSA) for single mode optical transmission was designed for the optical transceiver. Analytical studies were carried out to determine the effect of the attachment process and dimensions of laser diode and silicon optical bench (SiOB) on the coupling losses of the module. SiOB with V-grooves and U-grooves were fabricated with dimensional accuracies of $\pm 1 \mu\text{m}$. A single mode optical fiber (SMF) and a laser diode (LD) were passively aligned on the SiOB using optical adhesives and solder preforms respectively. Process related coupling losses due to the shifting of the fiber during the adhesive attachment and cure process have been demonstrated. Optical adhesive was also used as an index matching material to minimize reflection losses by filling the empty space between the LD and SMF. Refractive index and birefringence of the optical adhesive was studied under different temperature, humidity, and annealing conditions. Refractive index of the adhesive decreases at a higher rate for the temperature treatment compared to the humidity exposure. A sudden decrease in the rate of refractive index (thermo-optic coefficient, dn/dT), from $-2 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ to $-4 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ was observed near the glass transition temperature. Increase in refractive index of the adhesive was found to be directly proportional to increase in humidity and change in refractive index was found to be irreversible. Since the rate of

increase in refractive indices for TE and TM modes is not similar, birefringence (TE – TM) decreases with higher annealing temperature treatment of the adhesive. These changes in optical properties of the adhesive have been discussed in light of Lorenz–Lorentz equations.

Finite element analysis (FEA) was used to determine the misalignment between the optical fiber and the laser diode induced by thermo-mechanical stress. The fiber displacement within the V-groove at a given temperature was found to vary significantly for different thicknesses of adhesive layers which is present on either side of the fiber, but does not depend much on the total amount of adhesive used. FEA data was validated by the use of in situ micro moiré interferometry, to determine the displacement of fiber-centre in the V-groove when exposed to a temperature excursion ranging from room temperature to 125°C. Thermo-mechanical stress/strain behavior as a function of operational time of the module was modeled using the viscoelasticity property of the adhesive. Finally, an analytical model based on optics theory has been established to comprehend the results of FEA and the effect of stresses on the optical properties of materials so as to predict the optical coupling efficiency. Analytical results of optical coupling were subsequently correlated with experimental observations.

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Table of Contents

Abstract

Acknowledgement

Table of Contents

List of Figures

List of Tables

1. Introduction	1
1.1 Background	1
1.2 Motivation	2
1.3 Objectives	5
1.4 Major contribution of the thesis	6
1.5 Organization of thesis	6
2. Literature Review	8
2.1 Optical Network	8
2.2 Optoelectronic Packaging	9
2.3 EO Transceiver Module Packaging	10
2.3.1 Silicon Optical Bench (SiOB) Fabrication	11
2.3.2 Component-SiOB Attachment	12
2.3.3 Active and Passive Alignment Techniques	13
2.3.4 EO Transceiver module Package	14
2.4 EO Transceiver Module Optical Performance	15
2.4.1 Mode-field Mismatch	16
2.4.2 Optical components misalignment	19
2.4.3 Reflection loss at interface	21
2.4.4 Attenuation Loss	22
2.4.5 Dispersion	22
2.4.5 Polarization	23
2.5 EO Transceiver Module Reliability Failure	25
2.5.1 Reliability Testing Standards for Fiber-optics modules	26
2.6 Reliability of Optical modules in Temperature Environments	26

2.6.1 Materials properties characterization	28
2.6.2 FEA in Optoelectronic modules	30
2.7 Analytical modeling of optical coupling efficiency	32
3. Experimental Setup	34
3.1 Design and Fabrication of SiOB	34
3.2 Assembly of LD and SMF on SiOB	36
3.2.1 UV-curable optical adhesive	37
3.3 Displacement determination of optical fiber	37
3.3.1 Sample Preparation for micro moiré interferometry (MMI)	37
3.3.2. Fiber-shift measurement setup	38
3.3.3. Moiré pattern capturing	39
3.4 Refractive Index measurements of optical adhesive	39
3.4.1 OTDR	40
3.4.2 Prism Coupler method	41
3.4.3. Samples Preparation	41
3.4.3.1 Thermo-mechanical analysis	42
3.4.3.2 Temperature study	42
3.4.3.3 Moisture study	43
3.4.3.4 Annealing Study	44
3.5 Materials Characterization	44
3.5.1 Thermo-Mechanical Properties of Optical Adhesives Materials	44
3.6 Optical output measurements	46
3.6.1 Fiber-to-fiber optical coupling	46
3.6.2 Test vehicle output measurement	47
3.7 Experiment for optical alignment Reliability study	48
4. Materials Property Characterization of Optical Adhesive	49

4.1	Effect of environmental conditions on the refractive index of the adhesive	50
4.1.1	Dependence of refractive index on temperature	50
4.1.2	Dependence of refractive index on moisture content	52
4.1.3	Dependence of refractive index on annealing	53
4.2	Thermo-mechanical properties of optical adhesive	57
4.2.1	Coefficient of thermal expansion (CTE)	57
4.2.2	Modulus of the adhesive materials	58
4.2.3	Viscoelastic property of the optical adhesive	59
5	Fiber Misalignment Determination: FEA and Experiments	63
5.1	FEA Overview	63
5.2	FEA Model Development	64
5.2.1	Geometry	65
5.2.2	Material Properties	65
5.2.2.1	Optical fiber and Substrate	65
5.2.2.2	Optical Adhesive	66
5.2.2.2.1	Determination of Prony series	68
5.2.3	Load Step	70
5.2.3.1	Temperature loading (elastic model)	70
5.2.3.2	Thermal Cycling model	71
5.3	Fiber - Adhesive Joint in V-groove	72
5.4	Results	74
5.4.1.	Elastic modeling Results	74
5.4.2.	Displacement measurement Results	77
5.4.3.	Comparison and Discussion of FEA and Experimental Results	79
5.4.4	Fiber Misalignment due to Thermal cycle (Viscoelastic model)	80
5.4.5	Parameter sensitivity on the optical fiber displacement	85
6	Optical Coupling Efficiency Studies of Optical Module	88
6.1	Ray / ABCD Matrix	88
6.2	Coupling Efficiency Calculation	91
6.3	Analytical study of laser diode to single mode fiber butt coupling on SiOB	93
6.3.1	Effect of Mode Mismatch	94

6.3.2 Effect of uncertainty of SiOB dimensions	95
6.3.3 Effect of Attachment Process	97
6.4 Measured Optical Coupling Efficiency	98
6.4.1 Fiber to fiber coupling on Silicon Optical Bench	100
6.4.2 Laser diode to fiber coupling on the optical bench	101
6.4.3 Effect of index matching material on the coupling efficiency	102
6.5. Effect of Temperature Conditioning on Optical Coupling Efficiency	103
7. Conclusions and Future works	107
7.1 Conclusions	107
7.2 Future works	111
Publications (on PhD Research Work)	113
References	116
Appendix A: 2-D model to calculate the fiber displacement	127

List of Figures

Figure 2.1 Major Components in a point-to-point fiber transmission system	9
Figure 2.2 EO Transceiver assembly procedure	11
Figure 2.3 Enhancement of coupling between Fiber-LD by various method	18
Figure 2.4 Different type of misalignment between two single mode fibers	20
Figure 2.5 Polarization dependent loss	24
Figure 2.6 Birefringence Phenomena	24
Figure 3.1 Schematic of the designed Transceiver Module	34
Figure 3.2 Mathematical Calculation for Design of U-grooves and V-grooves	35
Figure 3.3 SEM picture of fiber-adhesive joint in V-groove for moiré interferometry joint of (a) sample 1 and (b) sample 2.	38
Figure 3.4 Schematic diagram of micro moiré interferometric setup.	39
Figure 3.5 Schematic of an optical fiber connector employing an index matching adhesive.	41
Figure 3.6 Refractive index measurement methods for different conditions temperature, moisture, and Annealing	42
Figure 3.7 Schematic of experimental setup for refractive index measurement with OTDR at different temperatures.	43
Figure 3.8 DMA multiplex method for TTS experiment	46
Figure 4.1 (a) Temperature (in ° Centigrade) dependence of refractive index. (b) Variation of dn/dT vs. temperature (b) $\tan\delta$ (DMA) graph for optical adhesive	51
Figure 4.2 (a) Variation of refractive index and percentage moisture with time for 120°C (b) Variation of refractive index (average of different samples) with moisture content for different temperatures.	52
Figure 4.3 Relationship between annealed temperature, refractive index and birefringence for both T_E and T_M modes for constant annealing time of 1 hour	54
Figure 4.4 Thermal DSC of samples annealed for 1 hour at different temperature. The trough areas of the thermal DSC correspond to the heat because of the change in short range crystallinity, which is increasing with annealing temperature.	55
Figure 4.5 XRD of optical adhesive annealed at different temperature.	55

Figure 4.6 UV-DSC plots for uncured and cured adhesive samples. Only the raw material is showing the heat flow change and cured samples don't show any change in heat flow	56
Figure 4.7 TMA of the optical adhesive	58
Figure 4.8 Variation of modulus of the optical adhesive with temperature	59
Figure 4.9 Multifrequency storage modulus curve for the optical adhesive	61
Figure 4.10 Master Curve at 70°C. C1 and C2 constant of TTS WLF model.	61
Figure 4.11 WLF shift factors	62
Figure 5.1 (a) A representative FEA model of the fiber-adhesive joint, with the fiber in the V-groove center. (b) Model is meshed with plane 13 element of ANSYS and region around the silicon-adhesive-fiber attachment is very fine meshed.	65
Figure 5.2 Temperature cycle for thermal loading	71
Figure 5.3 (a) Schematic of laser diode to single mode fiber alignment on silicon optical bench. Different possible situation of fiber-adhesive joint in V-groove (b) fiber in direct contact with inclined walls, (c) fiber not in contact with wall but in symmetry position, and (d) unsymmetrical position of fiber. (e) Different forces acting on the fiber at the time of curing process of adhesive. Note the adhesive layer thickness between the fiber and V-grooves wall gap as shown in Figure 5.3c and 5.3d.	72
Figure 5.4 SEM picture of fiber-adhesive joint in V-groove for moiré interferometry joint of (a) Sample 1 and (b) Sample 2.	72
Figure 5.5 (a) Fiber displacements (node at fiber center) calculated with respect to temperature for different adhesive thickness. (b) At temperature 125 °C, fiber shift with respect to the adhesive thickness.	75
Figure 5.6 Calculated fiber displacement shifts as a function of adhesive thickness between the fiber and the left wall of V-groove. Fiber is assumed to be in unsymmetrical position in the V-groove. Fiber distance from both the walls is considered same for the gap of 10 micrometer.	76
Figure 5.7. Comparison of Y-displacement for asymmetric and symmetric position of the fiber in V-groove.	77
Figure 5.8 Displacement of fiber center with adhesive area. Fiber is placed at a	77

distance of 10 micrometer from both inclined walls of V-groove.

Figure 5.9 Displacement Field a) X-direction and b) Y-direction for the fiber-adhesive joint sample 1 (Figure 2a)	78
Figure 5.10 Measured and calculated displacement of Fiber center of sample 1 (Figure 5.2a).	79
Figure 5.11 Measured and calculated displacement of Fiber center of sample 1 (Figure 2b).	79
Figure 5.12 Displacement of optical fiber center in X- and Y- direction over (a) 100 cycles (b) 12 cycles and (c) first cycle	82
Figure 5.13 Different FEA model elements selected to scrutinize stress around the optical fiber due to thermal cycle.	83
Figure 5.14 Stress developed at various elements (defined in Figure 5.13) in X-direction.	83
Figure 5.15 Stress developed at various elements (defined in Figure 5.13) in Y-direction.	84
Figure 5.16 Displacement of optical fiber center in X- and Y- direction over 100 cycles for temperature cycle from 25°C to 70°C.	86
Figure 5.17 Displacement of optical fiber center in X- and Y- direction over 100 cycles for dwell time of 2hrs.	87
Figure 6.1 Schematic of optical coupling with a lens	90
Figure 6.2 Beam waist variation for LD-Lens-Fiber system with different parameters (a) Fiber Lens Distance (b)Focal Length of Lens and (c) LD Lens. All dimensions are in μm .	91
Figure 6.3 Optical Coupling between Astigmatic LD and Single Mode Fiber	92
Figure 6.4 Coupling efficiency with misalignment for LD to Fiber butt-coupling (a) x-shift, y-shift and angular misalignment (b) z-shift (distance is measured in μm)	93
Figure. 6.5 Optical coupling loss due to the relative misalignment of laser diode and single mode fiber in silicon optical bench.	95
Figure 6.6 (a) Schematic of Fiber attached with adhesive in V-groove.	97
(b) Vertical misalignment corresponding to adhesive thickness (μm) as shown in	

picture a. (c)Optical losses caused by separation of the fiber from the V-groove sidewalls due to varying adhesive thicknesses.

Figure 6.7 Cross section SEM picture of U- and V-groove of fabricated SiOB **99**

Figure 6.8 Cross section of fiber in V-groove highlighting the gap between the the fiber and Si wall **99**

Figure 6.9 Histogram of optical coupling loss measurement for fiber-to-fiber alignment on SiOB for 12 samples. **100**

Figure 6.10 Histogram of optical coupling loss measurement for 30 optical module samples. **101**

Figure 6.11 Calculated coupling efficiency of the optical module is plotted against time for the 100 cycles. Initial coupling efficiency is considered to be (a) 25% and (b) 94%. Misalignment in X- and Y-direction was incorporated from the FEA data. **105**

List of Tables

Table 2.1 CTE of Optoelectronic Module Materials	29
Table 5.1 Thermo-mechanical properties of fiber-adhesive joint materials. SMF and Si properties are as reported in reference 4.	66
Table 5.2 Weighted function for Marquardt-Levenberg nonlinear regression	69
Table 5.3 The Prony constants for the regression	69
Table 6.1 Calculated Coupling Efficiency for different mediums	102
Table 6.2 Comparison of optical coupling efficiency analytically calculated and experimentally measured for the module after 100 cycles.	106

1. Introduction

1.1 Background

Since the 1990's, photonics and optics have become crucial for the development of various industries such as semiconductors, communication, bio-medical applications, entertainment industry, security, defense and laser therapy amongst others. Optics is a science that deals with the generation and propagation of light, and the changes that it undergoes and produces. Photonics deals with the properties and applications of photons especially as a medium for transmitting information. In 21st century **photonics** is expected to play a pivotal role for the development of diversified industries and will hopefully be involved in many research breakthroughs. The advents of optical fibers and lasers have revolutionized the way optics and photonics are applied in academic research as well as in industrial applications. Various applications and discoveries of optics are unexplored in its own field and also usages of optics as a research tool in different areas of science is unseen.

Optical communications is one of the areas where optical fibers and lasers are effectively used. It is growing fast, fuelled by ever increasing demand for bandwidths for local area network(s) (LAN). This demand cannot be met by using copper as it has almost reached its full potential. The optical carrier frequency in the range of 10^{13} to 10^{16} Hz yields a far greater transmission bandwidth than metallic cable systems (bandwidth up to around 500MHz). As conventional telecommunications and data transfer networks face increasing demand for speed of transmission and bandwidth, the all-optical network has increasingly become the technology of choice. Optical networks provide higher capacity and reduced costs for new applications such as internet, multimedia interaction, and advanced digital services. It is a generally accepted fact that an all-optical network may be the ultimate solution to fulfill the hunger for high bandwidths.

An optical network can be defined as a high-capacity telecommunications network based on optical technologies and components which provide signal routing, error correction, and signal restoration at the wavelength level. By creating many virtual fibers on a single physical fiber, Wavelength Division Multiplexing (WDM) has become one of the key

technology enablers of the optical network. By transmitting signals at different frequencies (or wavelengths), WDM enables co-existence of multiple signals on a single fiber just as though each signal was traveling on its own dedicated fiber. Since the mid 1980s, long haul (between various countries / over long distances) optical communications have become a reality with buried or submerged optical fiber lines stretching across the US as well as across the major oceans of the world enabling high speed voice & data transmission [1]. All optical communication in the wide area networks (WAN), metro area networks (MAN), and fiber-to-the-home (FTTH) applications will represent the next level of advancement in high speed, high bandwidth communications [2]. FTTH enables service providers to offer a variety of communications and entertainment services, including carrier-class telephony, high-speed internet access, broadcast cable television, direct broadcast satellite (DBS) television, and interactive, two-way video-based services. All of these services are provided over a passive optical distribution network via a single optical fiber to the home.

The backbone of an optical network is the suite of advanced optical technologies that perform the necessary all-optical functions. Most applications for fiber optics require two-way communications. This is achieved by using two separate fiber links for transmitting and receiving signals. Main components of the optical network are optical waveguide, transmitter (T_x), receiver (R_x), optical amplifier, and optical multiplexer-demultiplexer [3-5]. These different components are manufactured with assembly of different optical devices and electronics circuits on single platform. In order to achieve low cost and miniaturized modules, the recent trend in data links has been to develop an "Electro-optic (EO) transceiver module" by assimilating the two-way link source, detector, and associated electronics into a single device.

1.2 Motivation

In the microelectronics world, the term "packaging" typically refers to the encapsulation of the microelectronics chips into a form that can be easily connected to a circuit, while protecting it from assembly and test handling damage, as well as from the environment in

which it will eventually be used. In the optoelectronics world, optical chip has still not been made. Optical modules are made by assembling together different optical and electronics components/devices on a common platform. Thus, packaging in optical modules often combines the need to provide not only for electrical connection, mechanical support, and thermal management, but also, more critically, for an optical connection that is highly directional in nature and requires extremely precise control of positional tolerances between components. Thus, the scope of packaging optical modules is connection (optical and/or electrical), protection (thermal or mechanical) and manufacturing of devices. Optical components are classified as active and passive devices. Active devices are those requiring some sort of electrical connection like laser diode, photodiode, modulator, and amplifier. Passive devices are those that do not have any electrical connections and simply filter or route the signal based on wavelength, intensity, or polarization. The most critical aspect of packaging of any optical device is the optical connection between individual optical components.

Synchronization of various microelectronic, micromechanical, microoptic, optoelectronic, and fiber-optic components poses serious challenges in the packaging of transceiver modules. Packaging steps such as optical alignment of individual optical components dominate the product cost of Electro-optic (EO) transceiver module. Unlike electrical connections, the optical connections have some very interesting and challenging characteristics. The optical connections require extremely precise alignment and are highly sensitive to relative motions between the device and the optical components such as laser diode and fiber or lens and fiber. Even displacements to the order of a mere micrometer can render the component useless. Passive components often have many couplings, further complicating the assembly process. Costly equipment are available for aligning the different optical components to submicron levels on submounts, but these equipment add to the final cost of the modules due to their prohibitive cost. In order to address the cost of packaging, passive alignment technique has been the focus of interest. Another important consideration to cut the cost of optical modules is to use polymeric materials for fabrication of the components, and assembly materials. Technology and fabrication process is being developed to produce polymer

waveguide, polymer lenses, optical adhesive and polymer based active devices (such as laser diode, photo diode and optical multiplexer-demultiplexer) [6]. Polymer will not only cut the cost in term of materials, but also give more flexibility in terms of processing. It also gives a common material platform for assembling optical modules.

Microelectronic packaging has shifted from metal packaging to plastic packaging for cost-effective solutions. Molding method is utilized for the packaging of microelectronics chips with polymers. In the case of optical modules, if plastic molding method is to be used for packing purposes then the gap between two optical components should be filled with appropriate transparent materials. For transmitting the light signals with minimal loss, suitable medium is required. Molding materials will interrupt the optical power transmission from one component to others by coming in the gap. The Index matching materials are used to fill the empty gaps, which can make possible the plastic molding for the optical devices. Index matching materials are generally mixture of different polymers in fixed proportion. These index matching materials also serve the purpose of avoiding the reflection loss at the interface.

Polymer has its own disadvantages when compared to metal (Gold, silver and tin) and semiconductor (Silicon, Gallium Arsenide) materials. Polymers have a high coefficient of thermal expansion and their properties are time dependent; especially the mechanical properties, which are viscoelastic in nature. Optical misalignment failure that results in open optical circuits is a severe reliability concern because it degrades optical coupling which eventually destroys the entire module. Because optical alignment is one of the most important factors affecting the long term reliability of modules, understanding the mechanism of misalignment in optical devices and finding ways to suppress such failures is pertinent to overcome the challenges in the development of future polymer based optical technologies.

The effect of misalignment on optical coupling has been studied. Polymer viscoelastic properties and their impact on microelectronics have also been researched. However, the impact of viscoelastic relaxation on optoelectronic components and misalignment has not

been explored. Understanding the misalignment of the components in polymer based optical modules is significantly important for developing reliable polymer modules. Misalignment due to displacement, stress, materials mismatches and temperature excursions due to field operations etc. lessens the coupling efficiency of various components in EO transceivers. Thanks to the efforts in microelectronics packaging, methodologies have been developed to characterize the materials properties and stresses. However, methodologies for characterization of changes in optical properties due to stresses, moisture, temperature, polarization, and other effects important for optical transmission are yet to be fully understood and constitute an area of active research. Besides material property changes, optical coupling is also influenced by displacements, stresses, moisture, and temperature changes. Modeling tools for stress analysis are available; however, methodologies that combine non-linear optical effects, thermal, as well as thermo-mechanical packaging effects are required to meet the future design and performance requirements of optical networks.

1.3 Objectives

- a) Design and packaging of an EO module including SiOB design and materials selection for passive alignment and assembly:

To develop a passive alignment methodology, silicon optical bench design is optimized for self alignment of optical components. Since the overall consideration of this project is low cost module design and packaging, polymeric materials' selection for gapfill, index matching, and fiber attach operations has been undertaken.

- b) Characterization of optical and mechanical properties of EO packaging materials and to develop constitutive relationships for use in FEA and ray optics based modeling and simulation:

Methodologies to study optical properties (refractive index and birefringence) of optical adhesives exposed to temperature and humidity excursions were developed. Thermo-mechanical (elastic and viscoelastic) properties of adhesives are studied to facilitate the finite element analysis (FEA) of components subjected to reliability testing. The FEA data was validated by means of in situ micro moiré interferometry. The constitutive relationship developed for optical and thermo-mechanical properties

would be used in FEA and Ray Optics based simulation of module optical coupling efficiencies.

- c) To study the reliability of EO modules using FEA, ray optics, and laser diode / fiber assemblies subjected to thermal cycling:

Reliability of optical modules subjected to temperature cycling is studied experimentally and via FEA and ray optics based modeling. The model developed here incorporates viscoelastic effects, as well as optical property (refractive index, birefringence) variations upon environmental exposure.

1.4 Major contribution of the thesis

- New and original methodologies were developed to study optical properties (refractive index and birefringence) using prism coupling, OTDR, and fiber reflectance techniques. The effects of temperature, humidity, and time-temperature exposures were studied in detail.
- In-situ micro moiré methodology was developed to study the fiber-SIOB attachment with humidity, temperature, and time exposures. The moiré technique developed is the subject of a PCT patent (US Patent Application No. : 11/235,077) filed by NTU in September 2005.
- A comprehensive methodology to integrate constitutive relationships from optical and thermo-mechanical properties was developed using FEA and first principles ray optics to predict the optical efficiencies of EO modules
- A methodology to design and package low-cost all-polymer passive-alignment based EO modules was developed
- EO module reliability was studied upon exposure to thermal cycling stresses along with the comprehension of viscoelastic effects which are critical to all-polymeric EO modules

1.5 Organization of thesis

The present thesis consists of a total of 7 contributed chapters, including this introductory chapter. The materials included in this thesis, as was alluded to above, will cover the packaging for optical interconnection, including passive optical alignment

technique, reliability considerations for the optical alignment, materials property characterization both thermo-mechanical and optical, and optical coupling analysis. The second chapter gives a general overview of the optical module packaging and reliability. It includes a literature review on the research work in the field of passive alignment, optical coupling, materials characterization and optical module reliability. The third chapter describes the experiments' set up and experimental methods carried out in this research work. Chapter 4 covers the results and discussion on optical adhesive material properties characterization. Chapter 5 presents the finite element analysis method for the optical fiber displacement calculation in optical module counting the viscoelastic properties of adhesive materials and it is compared with micro moiré interferometry experimental results. Chapter 6 starts with the optical method development for the coupling efficiency calculation. It captures the result for the temperature cycle testing of the optical modules which is judged against optical coupling efficiency calculated by developed analytical method. Finally conclusion of this research work is presented in chapter 7 along with future recommendations.

2. Literature Review

2.1 Optical Network

It was discovered theoretically in early 60's that light could carry more information in a glass medium and at a faster rate than copper cable. The first challenge undertaken by scientists was to develop a glass so pure that information loss could be minimized. The breakthrough came in 1970, when Corning scientist Dr. Robert Maurer, Dr. Donald Keck, and Dr. Peter Schultz created a fiber with very little measured attenuation loss. This led the way to the commercialization of optical fiber technology [1-6]. Since then the technology has advanced tremendously in terms of performance, quality, consistency, and application. It further advanced with the first WDM introduction in 1994. The next few paragraphs present the fundamentals of optical fiber communications. There are many full-length books [3-5] on fiber communication for thorough reference.

A block diagram of a point to point fiber communication system is shown in Figure 2.1. An optical communication system (like all communication systems) consists of a transmitter, a communication channel, and a receiver. The transmitter converts the electronic signal to be transmitted into an optical signal. This operation can be performed either through direct modulation of light (shown in Figure 2.1.) or through an external modulator. Semiconductor laser diode (LD) or light emitting diode (LED) serves as the light source for the fiber systems. In direct modulation, electronic driving circuits modulate these sources. Photodetector converts the optical signal back into an electrical signal in the receiver module. PIN (p-i-n) photodiodes and avalanche photodiodes are used in the optical receiver. The receiver current is replica of the original modulating signal current. Optical amplifier boosts the optical signal without conversion to an electronic domain. Waveguide(s) serves the purpose of the communication channel.

Most communication applications for fiber optics require two-way communication. Normally this is achieved with two separate fiber links with separate transmitter, receiver and fiber link. The major market trends for optical systems are pushing for low-cost packages that integrate two or more discrete device functions in an increasingly small

Figure 2.1. Major components in a point-to-point fiber transmission system

footprint. In order to achieve low cost and miniaturized modules, a recent trend in data links has been to develop a “transceiver module” by integrating the two-way link source, detector, and associated electronics into one [7]. Current markets also demand efficient and reliable EO devices. Especially in the optoelectronics (OE) industry, where standardization is yet to come, these market forces challenge designers to use efficient, reliable, manufacturable packaging technologies.

In the following sections, a general review on optoelectronic packaging, EO transceiver module assembly, transceiver optical performance and package reliability will be presented. Lastly, thermo-mechanical modeling and optical modeling of module have been briefly discussed.

2.2 Optoelectronic Packaging

Packaging is done on many levels and serves many different functions. The basic function of packaging is to transfer energy (electrical, thermal, or optical) from one level to another. Traditionally, the first level of packaging is considered to be the interconnection of semiconductor or optoelectronic devices to some kind of leadframe [7-8]. The second level of packaging concerns itself with interconnection of the aforementioned leadframe to a circuit board, on which other package devices are also mounted. Transfer of electrical energy, thermal transfer, mechanical strength and electromagnetic effects are the common focal areas in packaging of microelectronics and

optoelectronic devices. In optoelectronic devices, another important area of concern is optical signal transfer. When making a packaging decision, one may need to make compromises and tradeoffs in each of these areas. For coupling of optical signal, splice and interconnect are required between various components of a device. Passive optical components are used for optical interconnect in optical networks, which do not require external power. Some of the important passive components are lens, isolator, direction coupler, optical filter, attenuator, circulator, mechanical switch, and polarization controller. By appropriately interconnecting them with active components (laser diode, receiver and waveguide), one can build many sophisticated communication systems, such as optical point-to-point trunk systems, optical subscriber loop networks, optical cable television systems, and optical Local Area Network (LAN) systems [3-4].

For optoelectronics, the requirements that drive device packaging revolve around some of the key characteristics of the system itself [7]. In single mode modules, the alignment tolerance of different optical components (for effective coupling) has to be greater than that in multimode system. These tighter alignments require certain packaging techniques that limit the user's choice of technologies. If the power budget allowed for packaging is constrained, efficient optical coupling is extremely critical.

2.3 EO Transceiver Module Packaging

The basic components of an EO- transceiver module are receiver (preamplifier, post amplifier, clock and data recovery (CDR) and demultiplexer (DEMUX)), transmitter (multiplexer (MUX), laser diode (LD), and EO modulator), waveguide and passive optical elements. To form a working unit, all of these components need to be precisely fabricated and aligned with each other while taking into account their individual optical, thermal and electrical requirements. Packaging these components presents a number of challenges specifically related to the optical aspects of the components. In general, packaging challenges for EO transceiver can be divided into (1) Physical size or geometrical, (2) material, (3) mechanical/thermal, (4) electrical, (5) optical, (6) assembly process, and (7) reliability and testing issue. Many of these issues are considered in great detail in the microelectronics context in a number of packaging books [8]. The packaging

procedure for EO transceiver using passive alignment technique (described in subsequent paragraph) is illustrated in flow chart of Figure 2.2. Different packaging steps are reviewed in the subsequent paragraphs.

2.3.1 Silicon Optical Bench (SiOB) Fabrication

Optical modules have been assembled on silicon substrate with various structures using different techniques primarily because it can be mass-produced with low cost process [7, 9-13]. The structural nature of silicon makes it possible to fabricate precise three-dimensional

Figure 2.2. EO Transceiver assembly procedure

shapes. Anisotropic etching of bulk silicon by using wet chemical etching is widely used in the fabrication of SiOB [11-13]. The technology for machining <100>- and <110>- oriented silicon by chemical etching is widely published in this literature [12, 14]. There are numerous chemical etchants like KOH (Potassium Hydroxide), EDP (Ethylene Diamine Pyrocatechol), and TMAH (Tetramethyl Ammonium Hydroxide) available for

machining silicon. Dry etching technique like RIE (Reactive Ion Etching) [15] and conventional Plasma etching [16] are also used for silicon micromachining. Some of the important factors with silicon micromachining are pattern alignment with $\langle 110 \rangle$ for getting smooth surface, compensating convex corner of the grooves, and photolithography on three-dimensional surface [17].

In case of microfabrication of SiOB, dimensional accuracy is important. Beside the three-dimensional accuracy, the surface roughness of the etched silicon ranging over $0.5\mu\text{m}$ causes a detrimental effect in the context of optical coupling. Generally, V shape trench is used in guiding the position of fibers in passive as well as active alignment. For fixing other optical components (such as laser diode, photo diode and lenses), either trenches of different shapes are fabricated on the silicon substrate or different techniques are applied.

2.3.2 Component-SiOB Attachment

The important design factors in EO transceiver module on SiOB are the reliability and durability of the passive (single mode optical fiber and lens) and active (laser diode and detector) optical components-to-silicon bond joint. Solder alloys have been successfully used for bonding, joining, and sealing the optoelectronic components in fiber-optics module [18-20]. Its joints function both as the electrical contact as well as the primary heat transfer interface between the die and the substrate. Solder electrical connection is better than wire connection due to its reduced size, electromagnetic noise, capacitance and inductance. The solder maintains mechanical joint for optical coupling. It has also been used for self-alignment of different components [20]. But, getting repeatability of the alignment from one module to another is difficult [18, 19]. Most of the studies on solder-assembled optoelectronic modules have focused on how to obtain high alignment accuracy rather than how to maintain the alignment obtained. Basic solder failure mechanisms are driven by temperature, moisture and voltage. A good review on solder technology in optoelectronic packaging has been presented in reference [22]. Presently flux- and pressure-free solder techniques of bonding are in use for better alignment accuracy [23].

In optoelectronics module, adhesive is replacing the solder technique, as the latter has inferior positional accuracy, requires costlier technique, and is unsuitable for light passing sections. Adhesive used in optical circuit is not only meant to perform adhesion bonding but also to provide high degree of light transmittance [24]. The basic requirements for adhesives are low shrinkage, low thermal coefficient expansion, fast curable, high adhesion strength and should match the refractive index of adhesive to material to be bonded. The physical and chemical properties of cured polymer depend on the extent of cure [25].

There are two types of optical joints in any optoelectronics module, joined sections that pass light (for joining optical path) and those that don't pass light (for precision bonding and moisture proof sealing). Passive components like micro lens and index matching gel are used in the light passing joint sections for efficient coupling of light in various components of the EO transceiver module. When laser diode is aligned with optical fiber or optical fiber is aligned with other waveguide, there is an air gap between two components in EO transceiver. Reflection of light takes place when there is a change in medium for light travel [24]. To minimize reflection at the unavoidable air gap between two light carrying elements, like two fiber faces, laser diode-fiber, or fiber-photo diode, the gap is filled with an index matching gel [26]. Optical adhesive has been synthesized with wide range of refractive index, and therefore acts as a substitute for index matching gel. Thus, optical adhesive is more advantageous than solder because it can be used in light passing sections.

2.3.3 Active and Passive Alignment Techniques

Alignment of micro-components such as LD, fiber, and photo diode with respect to each other is the most important constraint in the assembly of single mode EO transceiver module or any other single mode optical modules. There are two alignment techniques, active alignment [27] and passive alignment [28, 29], in optoelectronics industry. Active alignment, accomplished by powering optoelectronic components or otherwise passing light through them, generally requires careful, iterative movements of components to maximize the optical signal and thus optimize the coupling. Normally, this is a good way

to get the optimal coupling efficiency but cost of manufacturing is prohibitive due to high assembly cycle time and excessive use of precision machined parts. It is difficult and time consuming to align and hold optical and optoelectronic components to micron and submicron level tolerance where none of the six degrees of freedom of any of the parts are fixed [27].

Passive alignment techniques offer the capability of eliminating most, if not all, of the alignment uncertainties. Alignment is said to be passive when the alignment of one optical component with another is done without monitoring the alignment process by operating any of the active optical components. The passive alignment technique is hindered by higher insertion loss, longer processing time of parts and components and lower yield of packaging module [27]. So far, detailed investigations and developments based on passive aligning technology have been carried out to obtain a low cost mass production [28, 30]. The basic considerations of the passive alignment techniques are flip-chip bonding surface mount technology using the surface tension of molten solder [21,31], index alignment of optical devices with the marker [32] and mechanical contact alignment on the precisely fabricated planar light waveguide [33,34] or micromachined silicon platform [35]. Use of anisotropically etched silicon substrate (SiOB) for low cost passive alignment technique has been very promising for single mode optical modules assembly [35-37].

2.3.4 EO Transceiver module Package

Package provides mechanical and environmental protection to the device while providing the electrical interconnection between the device and the circuit board. Numerous kinds of package and its formats are available in the optoelectronic industry. The form factor of a package and its material makeup are driven by the application in which it is used. Package in the optoelectronic industry (same as microelectronic industry) can be divided into three categories; metal, plastic and ceramic [38]. Metal packages in the form of transistor outline (better known as TO cans) are used widely in optoelectronic industry. In the plastic package, the die is typically attached to a leadframe with any of the interconnection technologies [8]. The leadframe and device are then encapsulated using a

molding process. The molded plastic serves as the package of devices like LEDs. The ceramics packages come in variety of forms, such as DIPs, flat packs, chip carrier, and pin-grid arrays (PGAs) [7-8, 38].

2.4 EO Transceiver Module Optical Performance

In contrast to electronic packaging, optoelectronic devices involve light generation and detection and manipulation of light beams. In the environment of ever-increasing traffic levels and higher optical transmission speeds, it has become vitally important to ensure optimal light launch and propagation characteristics in order to achieve required link distance while maintaining consistent signal integrity. Therefore, issues related to optical coupling of interconnects need to be properly addressed. A brief introduction of emitted laser diode beam follows and optical coupling is discussed in detail thereafter.

The laser diode emits an optical beam whose profile is Gaussian in nature. Angular divergence parameters of Gaussian beam are defined by the wavelength of emission and the geometry of diode laser cavity. Gaussian beam doesn't change its nature while passing through optical elements so that the beam profile is always known throughout the path. Thus it is possible to estimate characteristics such as spillover, beam diameters, and illumination efficiency. The disadvantage with Gaussian beams is that the beam is assumed to be of infinite width [39].

An optical coupling system accepts optical power from an optical component, modifies it, and transfers the power to another. Coupling efficiency with which the power is transferred can be given by,

$$T = \frac{P_2}{P_1} \quad (1)$$

$$IL = -\log_{10} T \quad (2)$$

Where P_2 is the power transmitting into second component, P_1 is the power transmitting into first system and T is called transmittance, respectively. IL denotes insertion loss in decibel (dB) units. It includes coupling loss and attenuation loss. Guided wave coupling losses depend on the mode-field mismatch, optical components misalignments, and

Fresnel reflections [36, 42]. Coupling loss is related closely to the assembly process of the transceiver modules. Attenuation loss includes material absorption loss, medium bending and scattering loss. Light signal dispersion also affects optical performance of optoelectronic devices [40]. The more important issue in EO transceivers is polarization due to birefringence in index matching gel, and stresses in waveguide. These optical losses are reviewed in the following paragraphs.

2.4.1 Mode-field Mismatch

The term MFD originated after single mode optical components came into being. Spot size (SS) or mode field diameter (MFD) is defined as the distance between points where the strength of electric field of Gaussian beam is decayed to 0.37 (1/e) of the peak. It depends on parameters which affect guiding, such as the refractive index difference between the core and cladding, core diameter and wavelength. Typical values of MFD for telecommunication single mode fiber are around 10 μm at an operating wavelength of 1550nm and around 9 μm at 1310nm. The MFD plays key role in coupling among optical components. For efficient transfer of optical energy from one optical component to another, their respective mode field should overlap as much as possible [39, 43] and is depicted in Equation 3. The coupling efficiency between two Gaussian beams is expressed in terms of the mode fields of laser diode w_{LD} , and fiber w_{SMF} and also as a function of lateral, angular and longitudinal misalignment between the two wave guides:

$$\eta = \kappa \times \exp \left[-\kappa \left\{ \frac{x_0^2}{2} (1/w_{LD}^2 + 1/w_{SMF}^2) + \pi^2 \theta^2 [w_{LD}^2(z) + w_{SMF}^2] / 2\lambda^2 - x_0 \theta z / w_{AWG}^2 \right\} \right] \quad (3)$$

where

$$\kappa = \frac{4w_{LD}^2 w_{SMF}^2}{\left[(w_{LD}^2(z) + w_{SMF}^2)^2 \right] + \left(\frac{\lambda z}{\pi n_{gap}} \right)^2} \quad (4)$$

with

λ =wavelength

n_{gap} =refractive index of medium between laser diode and single mode fiber (SMF)

x_0 =lateral misalignment

θ = angular misalignment

z = longitudinal

If the wave travels within the optical fiber, the mode field diameter is constant due to the combining function of the fiber itself. At the end of the fiber, the optical field is not constrained and the field expands with increasing distance to the output facet of the fiber. The expansion of the field can be calculated by Equation 5.

$$w(z) = \sqrt{w_0^2 + \left(\frac{\lambda z}{2n\pi w_0^2} \right)^2} \quad (5)$$

where $2w_0$ = mode field diameter (MFD)

There is a great mismatch between the field parameters of fiber and laser diodes. Consequently, the optical coupling efficiency between these two devices is very low. The coupling loss (in db) between the two fields can be calculated, without additional mechanical misalignments, from Equation 3. Part of this is due to the fact that the emission pattern of laser diode beam is elliptical in shape [39]. A 1.5 μm semiconductor laser typically has a mode size of 1.5 μm ($1/e^2$ diameter) in the transverse direction and 2-3 μm in the lateral direction. The single-mode optical fiber is circular and has a mode size of 10 μm at 1.55 μm . The brute-force approach of simply butting an optical fiber almost against laser diode allows for only about a 10-20% coupling efficiency, or a 7 to 10 dB coupling loss. Mode field mismatch is the reason for low coupling efficiency. “Mode field transformers” can be used to couple the different mode fields, laser diode to single mode fiber [46, 47]. Examples of these devices are lenses or lens systems, as shown in Figure 2.3. The function of the transformer is to modify the emitting area of the light source to match exactly the core area of the single mode fiber end face. “Mode field transformers” can be used to couple the different mode fields, to 10 dB coupling loss. With these devices, a nearly perfect coupling between the two wave-guides is possible. Driven by cost constraints, several lens configurations have been proposed for optical coupling of laser diodes to single-mode fibers.

- a) A graded index lens (GRIN lens) is commonly used. A GRIN lens is very similar to a short length of graded index fiber (albeit with a much larger diameter).

Figure 2.3. Enhancement of Coupling between Fiber-LD by various method [5]

The lens collects and focuses the light onto the end of the fiber.

- b) A ball lens is also often used. This is bonded to the surface of laser diode with an epoxy resin that has a specific refractive index.
- c) The direct coupling method is also popular [48].
- d) Another common way is to fix a ball lens to the end of the fiber as shown in the Figure 2.3.

One can overcome the low efficiency of butt coupling by using lenses to better couple the two optical mode fields—a coupling efficiency of more than 90% has been shown. A disadvantage is critical part handling. There are several parts including one or two lenses, the fiber, and the chip, which must be handled for optical alignment. This handling results in the rather high cost of optoelectronic packaging.

2.4.2 Optical components misalignment

In determining the producibility and stability of the EO transceiver module, it is quite important to estimate the effects caused by misalignment in different optical components, because misalignment are inevitable both during and after assembly of the modules. In the assembly process of transmitter side of the transceiver module, monitoring photodiode, laser diode, lens and single mode fiber are held in order. Lateral misalignment caused by offset of lens can be largely compensated for by lateral adjustment of the fiber. On the other hand, after the transceiver module assembly, offsetting any coupling element from its initial position causes a direct effect in decreasing coupling efficiency. Coupling loss determines the required alignment tolerance for an alignment technique. Alignment tolerance for multimode devices is in few-micron ranges, whereas they are in the submicron range for assemblies involving laser diodes and single-mode devices [36, 44]. A number of techniques have been developed over the years for enhancing the alignment tolerance of different optical components for the assembly [37, 41, 42, 50-53]. In one of the recent efforts, two-beam optical interference has been used for enhancement of the coupling efficiency in laser diode to waveguide alignment [49].

There are several types of misalignment possibilities between a fiber optic source and a fiber optic receiver. In Figure 2.4, the typical 3 cases of misalignments are shown for SMF-to-SMF. Longitudinal separation occurs when the fibers have the same axis but have a gap s between their faces. Angular misalignment results when the two axes form an angle so that the fiber end faces are no longer parallel. Axial or lateral displacement results when the axes of the two fibers are separated by distance d .

Figure 2.4 Different type of misalignment between two single mode fibers.

By using equation 3, loss in coupling efficiency can be calculated for the different type of misalignments. Coupling efficiency between two Gaussian beams with the same w_0 mode field are expressed by equation 6.

$$\eta(x, \theta) = \exp\left(-\frac{x_0^2}{w_0^2} - \frac{\pi^2 \theta^2 w_0^2}{\lambda^2}\right) \quad (6)$$

Where, x_0 and θ are lateral and angular misalignments between two beams. Using the above equation 5, the tolerance for all coupling elements can be calculated by estimating the lateral and angular misalignments of the focused beams at the fiber endface, assuming that the focused beam spot size is equal to that for SMF. During assembly of the module, only the angular misalignment caused by lens offset x_1 must be taken into account. Under the confocal condition, lens offset x_1 from the optical axis brings about the angular misalignment defined by $\theta = x_1/f$.

Axial displacement is the most common misalignment occurring in practice, which also causes the maximum power loss. This axial offset reduces the overlap area of the laser diode and single mode optical fiber end faces and consequently reduces the amount of optical power that can be coupled from laser diode into the optical fiber. A technique to

reduce the lateral misalignment is to first attach the lens to the laser diode to produce a collimated beam in free space. The lens may be either permanently attached to the laser diode or attached via an industry standard connector. The issue then is to align the collimated beam from the free space optics with the collimated beams produced by the laser diode. By working with collimated optics, the distance between the laser diode and the optical fiber is not a problem.

2.4.3 Reflection loss at interface

When light is incident on the boundary between one medium and another, part of it will be reflected away from the boundary and the rest will be transmitted across the boundary and into the new medium. The light that is transmitted into the new medium will generally experience a change in direction due to refraction. The percentage (R) of the incident light amplitude that is reflected can be calculated using the Fresnel equations (7).

$$R = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2 \quad (7)$$

The transmitted power is just the difference between the incident power and the reflected power, so for the air-SMF boundary approximately 94% of the incident power is transmitted. Percentage reflection also depends on incident angles and polarization of incident beam [54]. When coupling light into the single-mode optical fiber, the incident angles of interest are limited to $\theta_i < 10^\circ$. For this range of angles the reflection is approximately constant and independent of polarization.

Modulation characteristic for laser diode modules are greatly affected by the light reflected from coupling elements and connection ports in the transmission fiber line. The light from coupling elements, in particular an SMF endface positioned near an LD, varies the output power ration between the forwarded light into the SMF and backward light into the monitor photodiode. In addition, the oscillation spectrum is jumped greatly by the reflected light, a phenomenon distinguished in the case of microlens coupling method because of its large resonance-frequency separation of the external cavity [55].

Reflection from the planar surfaces perpendicular to the optical axis is particularly bad in respect to reflection [55].

2.4.4 Attenuation Loss

The light signal is lost from a beam as it travels through the core from the input end to the output end of the waveguide. This light loss is described as the attenuation (power loss) rate. The cause of attenuation may be divided into three separate categories. The first, called material absorption, is due to absorption of optical energy into the electronic energy levels of materials or into vibrational levels of different bonds in material. In this case, energy is absorbed from the optical beam and reradiated into the molecular lattice in the form of heat. The second type of attenuation is due to bending losses of which there are two types. One is due to regular bending of the entire waveguide at nominal radii. The second, referred to as micro-bend loss, arise because of random variations in the direction of the axis of the core. These may even be microscopic, due to external forces, imperfections in the coating or cladding, ripples in the core-cladding interface, microcracks, and other causes. In either case, light will be injected from the core into the cladding, and thus cause a decrease in the light intensity transmitted through the core to the output end of the waveguide. Finally, there are scattering losses. Scattering can be defined as diffusion of reflected electromagnetic energy in all directions. Scattering can be classified as Rayleigh scattering, Brillouin scattering and Raman scattering [6].

2.4.5 Dispersion

Dispersion is a major concern in communication systems. It refers to the process that causes different components of the light signal to be affected differently. In particular, the speed at which the different components are propagated along the waveguide or any medium can vary enough to result in significant different transmission delay or arrival times for the various portions of signal. The outcome is distortion of the signal when it is reconstructed from all its components at the receiver. Various type of dispersion can take place in EO transceiver module like modal dispersion, material or chromatic dispersion, polarization mode dispersion and waveguide dispersion [3]. Significant dispersion of

light in transceiver can occur depending on the material used in device and the working condition. Dispersion effect becomes more significant as with increasing distance [56].

2.4.5 Polarization

Polarization is firm evidence of the transverse nature of light. Polarization is defined in terms of pattern traced out in the transverse plane by the electric field vector as function of time. It is not always possible to describe light in term of predictable electric field vector. Light from a laser diode is almost completely polarized, presenting both opportunities and challenges in sensor and telecommunications applications. Polarization dependent loss (PDL) and polarization mode dispersion (PMD) are two most important challenges in optical communication related to polarization nature of light. Polarization dependent loss is a measure of the peak-to-peak difference in transmission of an optical component or system with respect to all possible states of polarization. It is the ratio of the maximum and the minimum transmission of an optical device with respect to all polarization states (Figure 2.5).

$$PDL_{dB} = 10 * \text{Log} \left[\frac{P_{MAX}}{P_{MIN}} \right] \quad (8)$$

PMD occurs when different planes of light inside a waveguide travel at slightly different speeds, making it impossible to transmit data reliably at high speeds. In simple word, when the light traveling along one polarization axis moves slower than the light polarized along the other axis, this effect can spread the pulse (see Figure 2.6). Some times spreading the pulse is enough to make it overlap with other pulse or change its own shape enough to make it undetectable at the receiver. It can distort signals, render bits inaccurate, and destroy the integrity of a device or network. PMD is the single biggest challenge in optical network with increasing speed for long distance communication. The PMD is measured in term of time of separation of polarized energy known as differential group delay (DGD). Polarization can take place by different processes: (a) selective absorption, (b) reflection, (c) birefringence, and (d) scattering [57].

Figure 2.5. Polarization Dependent Loss

Unpolarized light incident on a refringent material splits into an ordinary (O) ray and an extraordinary (E) ray. These two rays are polarized in mutually perpendicular directions (drawing not to scale)

Figure 2.6. Birefringence Phenomena

2.5 EO Transceiver Module Reliability Failures

EO transceiver module is assembled of micro-optic (lens), micromechanical (SiOB), optoelectronic (LD and PD), microelectronic (integrated circuit) components and different type of supportive materials (solder, adhesive, and index matching gel). The packaging and assembly of the transceiver must be amenable to high volume manufacturing and low cost to meet the increasing demand for fiber optic communications in consumer market. After packaging next important consideration factor is the reliability and durability of the different components and different components joined. Optical modules requires to operate for longer periods of time, over wider temperature ranges and in higher vibrational and accelerations environments.

EO transceiver module failure can happen due to electrical, mechanical or optical reason. Most of the Electrical and mechanical failure of optoelectronic device take place due to same reason as microelectronic device failure mechanism [8]. In case of optoelectronics module optical failure is more severe and requires special attention. Misalignment of different optical devices relative to each other can result in optical power loss and cause optical failure of the module [58]. Many studies have been carried out on the sensitivity of several schemes to lateral displacement and longitudinal displacement between the diode and lenses or single mode fiber. Analytical modeling has been done for fiber to laser diode considering the field of fiber as symmetric and taking laser diode field as elliptical. Both the fields are described by Gaussian beam equation [60, 61]. Results are consistent in all of these reports regarding different types of offsets like X offset, Y offset, and pitch offset. Within a micron or degree offset the coupling efficiency decreases drastically. A theoretical investigation has been carried out for the coupling efficiency of a laser source connected to a singlemode, step-index fiber, with an upside-down tapered lens on the fiber tip. It has been shown that a loss of 0.74 dB for 2-mm transverse misalignment. For an angular misalignment of 2° , coupling loss is at 1.96 dB [62]. In both cases, loss without misalignment was found to be at 0.1 dB, which corresponds to 97% efficiency. More fiber-lens-LD systems coupling loss due to different types of misalignment has been studied and found to have similar effect on coupling efficiency as mentioned above [53,54]. Large misalignment tolerance implies

the positioning process in packaging of a laser diode module can be simplified, which may also lead to cost saving and a more reliable module.

2.5.1 Reliability Testing Standards for Fiber-optics modules

Environments have an important impact on the stresses experienced by a device with a resulting consequence on reliability if the device is not sufficiently robust. The reliability assurance criteria are, therefore, to be associated with the particular environment in which the optical module is expected to operate. To date, the main standards for optical modules originate from Telcordia (formerly Bellcore) of the US, and largely restrict themselves to the reliability and environmental requirements of fiber-optic components [59]. The Telcordia standards may not be realistic for very-low-cost applications, particularly for those devices with shorter lifetime expectations. Many Telcordia and JEDEC package standards need to be modified to meet the needs of optoelectronic packages. Room temperature vulcanizable silicone resin gets easily hydrolyzed in an 85/85 temperature / humidity test, which leaks off the hermetic package. This phenomenon apart from causing loss of hermeticity, and impairs solder-ability by virtue of residues [59]. With this in mind, a number of organizations, including the IPC [112] (formerly the Institute for Printed Circuits) and the Telecommunications Industry Association (TIA, USA), are looking at the creation of revised reliability specifications for low-cost optoelectronics modules.

2.6 Reliability study of Optical modules

For optical modules using SMF-adhesive joints, it is very difficult to suppress degradation due to temperature cycles and humidity because the shearing tension displacements, caused by thermal expansion differences and inner stress, are apt to occur. Performance of the adhesive joints in the transceiver module is dependent on the properties of the optical adhesive, which, in turn is affected by environmental conditions (such as temperature and humidity). The performance of adhesive joints needs to be studied in detail for different systems in various testing conditions (like temperature and humidity). It has been found in general that the stability and the reliability of the fiber-adhesive bonds are a major concern in optical modules [63-64, 65]. Mechanical

reliability problems are mainly induced due to the large shrinkage during the curing process [65-66], the high coefficient of thermal expansion (CTE) of the adhesives and high moisture absorbing nature of the polymer materials. Adhesives, which are made of polymer materials, have a coefficient of expansion that is an order of magnitude greater than the solder material. Large amount of elongation and contraction can take place in the adhesive joints due to the variation in the temperature and humidity. Because the CTE of the silicon substrate and the fiber is very low, the fiber movement would be mostly governed by the expansion and contraction of the adhesive. Due to this, misalignment is more probable in the optical fiber attached with adhesive.

Thermal stresses have been the subject of much study in the last 70 years. Thermal stresses in bimetal systems have been widely examined [67]. Analyses of increasing complexity followed, considering systems with interfacial cracking [68], more complicated geometries [69], and transverse stress considerations [70, 71]. All of these analyses applied to systems containing no components with time- or temperature-dependent material properties. Investigation of temperature- and time-dependent behavior of polymeric material systems subjected to thermal changes is widely available. A good analytical overview can be found in papers [72, 73]. Thermal cycling as a source of damage in material systems has been reported for a wide variety of situations. Failure in plastic packaging [74], solder joints [75], and thermal barrier films [76] has been attributed to thermal cycling, but without specific mechanisms of failure being identified. Thermal fatigue [77] and thermal ratcheting [78] are two failure mechanisms that have been identified in materials subjected to the thermal cycling - the former describing incremental crack growth in constrained materials and the latter defining plastic strain accumulation in metals cycled at very high temperatures. An analytical study of the effect of thermal cycling on elastic bimaterial systems has been presented [79]. Thermal cycling effects and non-linear material response are considered together in some works. One of the reference papers contains closed-form and finite element elasto-plastic analyses of layered materials subjected to thermal cycling [80]. Inelastic strain accumulation in short fiber metal matrix composites during thermal cycling has been

considered [81]. A study of the thermo-viscoelastic response of graphite/epoxy composites during thermal cycling has been also reported [82].

In optical modules, there are many factors involved in the adhesive-fiber joints such as design of the optical assembly platform, the amount of the adhesive and the adhesive material properties, which may be responsible for the fiber shift under temperature cycling and moisture absorption. Furthermore, the order of the fiber shift is quite small, in the submicron range. It is difficult to measure a submicron level shift in the fiber during thermal loading. Thus, it is very hard to identify the factor which contributes most to the fiber shift during the thermal loading. The thermally induced fiber shift of fiber-solder-ferrule (FSF) joints in dual-in-line package (DIP) have been studied experimentally and numerically [83]. It is suggested to place the fiber in the center of ferrule to reduce the fiber shift of FSF joint in laser diode packaging based on the study.

2.6.1 Materials properties characterization

For predicting the optical loss of EO transceiver module in temperature and humidity conditions, optical, thermal, hygroscopic and mechanical properties of different materials are needed to be studied. Some of the important properties are briefly discussed below [85].

Refractive Index (RI): RI of material, such as lens, index-matching gel and waveguide through which light is guided, is important. Sudden change of refractive index can increase the reflection of light at the interface. RI of polymer material is very sensitive to temperature (thermo-optic (TO) property). The refractive index of polymers decreases in temperature at a rate of -10^{-4} $^{\circ}\text{C}$, which is one order of magnitude larger than that of inorganic glasses [87]. The TO property made polymers attractive material for use in the optical switches [86, 88], but in case of transceiver high TO is not desired. Temperature dependency of RI of polymer has been reported using various techniques like Fizeay fringe [89], deflection of prism [90], Mach-Zehnder interferometer [91] and grating coupling [92].

Birefringence: Some of the materials have different refractive index in different direction. This is known as birefringence. Upon entering a birefringent material, unpolarized light splits into two plane-polarized rays that travel with different velocities, corresponding to two angles of refraction, as shown in Figure 2.6. The optical properties of polymer films can be altered by stretching it. Under normal (unstressed) conditions, if the polymer chain molecules in the film are oriented more or less at random throughout the material, the film will be optically isotropic. But depending on the nature of the applied stress, the polymer chains may be stretched out in a way which alters the polarization state of light transmitted through the material.

Birefringence can be expressed as the sum of three components in polymer devices: [93]

- a geometrical component determined by shape,
- the self-stress component, determined by the difference between the thermal coefficients of different contact materials like different core and cladding material of waveguide, and polymeric lens-adhesive;
- the outer stress components, determined by the stress-applying parts.

Modulus [94]: A quantity or coefficient, which expresses the measure of some specified force, property, or quality, as of elasticity, strength etc of material. It is an important parameter in determining the failure of EO transceiver module. Modulus of material determines the stress/strain developed in material due to thermal or mechanical loading.

Coefficient of Thermal Expansion (CTE): The coefficient of thermal expansion is defined as the fractional change in length or volume with unit change in temperature. Plastic materials have higher CTE than metal and ceramics (Table 2.1). The difference in the coefficient of thermal expansion develops internal stress and stress concentration in packaging materials. Misalignment can come at high temperature due to high CTE of adhesive or waveguide materials [84, 94].

Table 2.1 CTE of Optoelectronic Module Materials [84]

Materials	Coefficient of Thermal Expansion (CTE)
Silicon	2.6×10^{-6}
Gallium Arsenide	6.86×10^{-6}
Polymer	$4.0\text{-}13.0 \times 10^{-5}$

Glass Transition Temperature (T_g) [94]: The glass transition temperature (T_g) is the temperature at which a material changes from a hard, glassy substance to a soft rubbery one. Physical material properties such as dimension, volume, and coefficient of thermal expansion (CTE) increase after this transition region. For polymeric materials CTE increase by an order in magnitude above T_g. Materials used for packaging of EO transceiver module must have high T_g to be functional in wide temperature range.

Moisture Absorption: The tendency of plastics to absorb moisture cannot be overlooked since even the slightest amount of water can significantly alter some key mechanical, electrical, or optical property. Water absorption characteristics of plastics depend largely upon the basic type and final composition of a material [87]. Moisture absorption can cause swelling that may lead to microcrack or mechanical failure of module. Baking can remove the moisture from the bulk, but the cracks do not self-heal. Humidity dependence of the refractive index of polymers has been reported [87]. The humidity dependence of acrylic polymer was found to be as large as $10^{-5}(\% \text{ RH})^{-1}$, some hydrophobic polymer, such as silicon resin and fluorinated epoxy resin were affected by humidity to a much lesser degree.

2.6.2 FEA in Optoelectronic modules

In order to evaluate the optimal combination of material and support geometry, which minimizes the stress/strain induced in the optoelectronics module, a complete investigation based on experiments and finite element analysis (FEA) is required. The stress/strain is supposed to be induced on the structure from the thermal, and humidity

loading, as discussed above. Within the microelectronics packaging community, FEA is often used to predict stress as an assembly is subjected to thermal cycling [94-96] and humidity conditioning.

Finite element analysis was developed in the early 1960's with key feature of describing parameter values at each node [97]. FEA allows one to investigate many scenarios through simulation in the early design stage where most of the errors are bound to occur without carrying out actual prototype. The FEA technique is also used to analyze the thermal and mechanical behavior of complex structures in a given system. According to this methodology the domain of interest in a given structure is first subdivided into a discrete and finite number of elements. The stresses which influence various properties of the material elements are applied in conjunction with the variation principle, to transfer the boundary value problem into a system of simultaneous algebraic equations, which are then solved for a desired parameter. Division into discrete finite elements enables modeling of complex geometric boundaries using higher order elements. The computation complexity, as per the nature of the problem, demands considerable computational time and effort. Many high-technology companies have developed commercial software tools for different applications like mechanical, thermal and fluid dynamics problems [98].

For the optoelectronic modules, finite element analysis of stress has been done in different parts of package like fiber-silicon submounts attach, LD-solder bond and fiber-laser alignment. The choice of adhesive/soldering material for the LD or fiber bonding is important to minimize the stress at the adhesion point [99]. If the laser needs to be used along with Polarizing Maintaining Fiber (PMF), any stress on the fiber would cause the extinction ratio of the fiber to change, which affects the laser performance [100]. LD operating characteristics such as threshold current, wavelength, and the lifetime of the device have been observed to be dependent on mechanical stress [7]. FEA analysis of different structures was done to simulate the stress in the fiber and the solder in order to limit the stresses in the design. The size and shape of the fiber-to-silicon bond joint was tried to optimize with nonlinear FEA for different solder materials (80Au20Sn and

96.5Sn3.5Ag) [99]. Thermal stress in optical component like waveguide, lens and index matching gel can be large enough to cause substantial changes in RI to create optical anisotropy. Finite element method was used to study the stress-induced birefringence in waveguides [101]. Another key research topic for the study of reliability in optoelectronic packaging, as discussed earlier is fiber alignment shift due to thermal and/or humidity loading. The FEA study was carried out to provide useful design guidance for understanding and evaluating the possible fiber alignment shift under the temperature cycling test for optical module packaging applications [102].

Many software tools like, ANSYS, ABAQUS, NASTRAN, and LUCAS are available to study the effect of thermo-mechanical stress on new package designs. These package designs can be optimized for the specific environment and the physical properties of the materials under consideration using software tools. ANSYS was used for analyzing the thermo-mechanical effect in EO Transceiver module. The ANSYS code is versatile finite element analyzer that can handle linear as well as non-linear problems, both in steady state and transient conditions [103]. It also has pre and post processing capabilities, and was used in this study. Similar capabilities and results are expected from other commercially available FEA software tools.

2.7 Analytical modeling of optical coupling efficiency

The optical coupling efficiency, in conjunction with variations in efficiency arising from system tolerances, is a key parameter for evaluating the optical performance of an optical transceiver [104, 105]. Selection of appropriate optical simulation method for the optical transceiver module depends on the type of components in the module and the accuracy required. Ray tracing model [39] and diffraction-based model [106] were used for determining optical efficiency according to requirement. Gaussian optics (ray-tracing method) are suitable for paraxial situations [39], but one should use a more complete description such as Rayleigh-Sommerfeld diffraction calculation (diffraction-based model) [106] when deviating from paraxial conditions. But accurate, direct integration of the Rayleigh-Sommerfeld formulation is time consuming.

Various methods of analyzing coupling efficiency of optical fiber and LD using Gaussian optics [60-62] have been proposed for different situations. Gaussian optics use ABCD law for tracing the laser beam shape at different positions. Gaussian optics will be discussed in detail in numerical analysis chapter. The motive for all these studies is to enhance coupling efficiency and misalignment tolerance of packaging laser diode modules. The theoretical positioning of a single-mode fiber in coupling light from circular laser beam [107] and astigmatic laser beam [61] were dealt with. Gaussian optics method is adopted for determination of power loss (with a criterion of 3 dB) with regard to various misalignments for the targeted coupling efficiency. An analytical beam propagation approach to multimode fiber coupling modeling was presented, which models mode power and phase distribution from first principle (unlike ray-tracing) [58]. Optical model was presented for different situations of enhancing the coupling efficiency by using discrete components such as ball lens [108], GRIN lenses [109], and cylindrical lenses [61], or integrating the lens with a fiber such as hemispherical lensed fiber [109], and hyperbolic lensed fibers [60]. The coupling efficiency calculation for different types of misalignments like transverse and angular was done in detail for various laser-diode package systems [111].

3. Experimental Setup

Schematic of EO transceiver module on SiOB has been shown in Figure 3.1. Different optical interconnects of module are laser diode to waveguide, waveguide to waveguide, waveguide to detector. To study the optical reliability of interconnects, a test vehicle has been designed in such a way that its results can be correlated directly to that of other interconnects. Test vehicle is based on laser diode to single mode optical fiber alignment and these components are mounted on SiOB. Laser to the optical fiber coupling is more critical than the fiber to detector coupling because of larger active area of the detector [7]. The fiber to detector (photo diode) coupling can be analyzed with the help of LD-fiber coupling results. Effect of index matching materials on the coupling efficiency of interconnects can also be studied with the same SiOB.

Figure 3.1. Schematic of the Transceiver Module being designed as part of this research project

3.1 Design and Fabrication of SiOB

Silicon Optical Bench structures were designed and fabricated for a laser diode to single mode fiber passive alignment. The SiOB design (Figure 3.2) included V-grooves for self-positioning of optical fiber and U-grooves for laser diode (LD) mounting. The geometry of V-groove and U-grooves were determined based on bare single mode fiber (cladding=125 μm) and LD chip ($250\pm 10\mu\text{m}\times 250\pm 10\mu\text{m}\times 100\pm 7\mu\text{m}$) dimensions. Dimensions of laser diode chips and single mode fiber (SMF) were measured using a high-resolution optical microscope. The laser diode has a dimensional uncertainty of

$\pm 10\mu\text{m}$ in the height plane and $\pm 2\mu\text{m}$ for the active area with respect to upper surface. This is one of the main barriers in adopting passive alignment for optical module assem-

Figure 3.2. Mathematical Calculation for Design of U-grooves and V-grooves

-bly. To find the minimal coupling loss due to the dimensional uncertainty of the chip, the width of U-groove is varied ($320 \pm 10\mu\text{m}$). V-groove dimension is determined with the help of U-groove dimension, chip light emitting point and fiber core-cladding size. A four -wavelength transmission channel using similar techniques for transmitter and receiver OSAs has been reported recently [118].

The SiOB has been fabricated on a silicon wafer with (100) as the etching plane [34, 37]. Since the optical bench has varying depths to accommodate the LD and the fiber, three-step etching technique is required for the self-aligning process. Three different masks were used to construct the SiOB for the test vehicle fabrication. In order to avoid the positioning error between LD and fiber, the formation of etch patterns of grooves was made by one single photolithography process. The silicon wafer was anisotropically etched using KOH solution in isopropyl alcohol (IPA) at 70°C and Tetramethyl Ammonium Hydroxide (TMAH) solution. Initial fabrication trials resulted in up to 10 μm deviation of SiOB dimensions from the designed values. This deviation could have occurred due to lack of pattern alignment with the $\langle 110 \rangle$ direction, etching rates of Si by KOH or TMAH, deviation of mask dimensions from design dimensions, and variations due to undercutting in the $\langle 111 \rangle$ direction. Etching rate was optimized by controlling several factors such as etch direction into the Si lattice, temperature of the etching chamber, KOH-H₂O concentration over the duration of etching, and Si wafer doping. After optimizing the etch process, the dimensional deviation in SiOBs was reduced from 10 μm to 1 μm .

3.2 Assembly of LD and SMF on SiOB

After optimizing the SiOB dimensions and fabrication process, the attachment process of laser diodes using solder and fibers using adhesive were optimized on the SiOB. The final position of the LD chip within the recess depends on the volume of solder used in the die attach process. If the volume of solder is less, the laser diodes may not physically bond with the SiOB, while excessive volume may cause transverse and lateral misalignments. This attachment process problem can contribute significantly to the misalignment of optical components. This problem was avoided by using Au80Sn20 solder preform of precise volume required for laser diode attachment. The Au80Sn20 solder preform used was of a dimensional accuracy of $\pm 1 \mu\text{m}$. After placing the chip and solder preform in the U-groove, the SiOB was heated until above the solder melting point of 290°C to form the metallurgical bond. A finite pressure was applied on the chip to make the molten solder flow faster and keep the LD in contact with the silicon wall.

Following the LD attachment, a single mode optical fiber was attached to V-groove using an UV-curable adhesive (described below). The optical fiber was cleaved and cleaned properly to minimize reflection losses and to attain better coupling efficiency. It was then positioned in the V-groove in close axial proximity with the laser diode. To avoid the initial misalignment of fiber from the V-groove during adhesive attach, fiber was pushed down during the 40 s UV-curing process so as to bring it in contact with the walls of V-groove. The amount of adhesive was controlled with the help of an automatic dispenser since extremely small amount of adhesive is required to fill the micrometer sized V-groove.

3.2.1 UV-curable Optical Adhesive

The optical adhesive used in the study is ABLELUX OGRFI146T which is manufactured by Ablestik. This adhesive is acrylate-based, consisting of oligomers, monomers, additives, and photoinitiators and is therefore suitable for use in the light passing section in optical modules. These formulations can be modified to provide optically clear resins for specific requirements of different properties, such as refractive index and adhesion.

3.3 Displacement determination of optical fiber

Displacement of optical fiber in the assembled module was measured during the thermal and humidity loading. Micro moiré interferometry was used here because it is a non-destructive optical technique. Micro moiré interferometry (MMI) is an optical technique that can determine in-plane displacement components with nanometer sensitivity [119]. Measuring the fiber displacement helps in verifying the finite element code developed for analyzing the component misalignment in optical system.

3.3.1 Sample Preparation for micro moiré interferometry (MMI)

For MMI, the specimens were prepared to reveal the silicon substrate, optical fiber and adhesive bond interfaces. The laser diode module was carefully ground and polished to reveal the area of interest. The SEM picture of specimens, after grinding and polishing, shows the initial position of the fiber in the V-groove for two samples (Figure 3.3a and 3.3b). It should be noted that the adhesive layer thicknesses between fiber and inclined

Figure 3.3. SEM picture of fiber-adhesive joint in V-groove for moiré interferometry joint of (a) sample 1 and (b) sample 2.

walls cannot be controlled and are not the same for the samples. A crossed line diffraction grating was transferred to the interface by the replication technique [119]. A thin layer of a transparent adhesive (BA-F114) was used for sticking the grating on the samples. There is no initial temperature history in the fiber-adhesive joint because of the room temperature curing adhesive used for the grating transfer. The diffraction grating has a frequency of 1200 lines/mm and is cross-line grating with orthogonality within $(\pi/2 \pm 0.5 \times 10^{-4})$ radians.

3.3.2. Fiber-shift measurement setup

A schematic of the micro moiré interferometer is shown in Figure 3.4. The specimen grating interacts with the virtual reference grating, formed by two-beam interference, to generate moiré fringe patterns. The virtual grating, also known as reference grating, controls the sensitivity of the measurement. A 30mW Helium Neon laser (wavelength 633nm) with a split fiber coupler is used to produce a virtual grating of 2400 lines/mm in the plane of the fiber adhesive joint. The SiOB is mounted on a three-axis translation aluminum stage with heater. The temperature controller, which consists of a solid-state relay and a proportional integral differential controller, is used to control the temperature of the specimen on the heating block.

Figure 3.4 Schematic diagram of micro moiré interferometric setup.

3.3.3. Moiré pattern capturing

The samples were heated using the hot plate from room temperature (23°C) to 100°C as shown in Figure 3.4 to simulate the temperature cycling profile. The thermocouple attached directly to the sample provided feedback to the temperature controller. This special arrangement helped in maintaining the quality of fringe pattern by avoiding any thermal drift in the environment near the specimen surface. The temperature of the sample was allowed to stabilize for 10 minutes before the moiré patterns were captured. The displacement components in the X and Y directions were recorded at temperatures of 40°C, 60°C, 80°C, and 100°C. The numbers of moiré fringes in the region of interest (optical fiber-adhesive joint, approximately 200µm in width, and height each) were insufficient for analysis. Thus, carrier fringes were added before thermal loading, to realize the displacement components in the X and Y direction with better accuracy and precision.

3.4. Refractive Index measurements of optical adhesive

Optical adhesive used for the assembly of the module is used as an index matching materials between the laser diode and optical fiber. The changes in refractive index of the adhesive due to different environment conditioning (such as temperature, humidity and

annealing) was determined with the help of optical time domain reflectometry (OTDR) and prism coupler. Dynamic mechanical analysis (DMA), differential scanning calorimeter (DSC), Thermal gravimetric analysis (TGA), and X-ray diffraction (XRD) of the adhesive were carried out to understand the cause of changes in refractive index under different environmental conditions.

3.4.1 OTDR

An OTDR based on the principle of Michelson's interferometer is used to determine the optical return loss at the fiber-adhesive interface. OTDR is a nondestructive technique capable of performing *in situ* measurements and requires access to only one end of the fiber. It injects a short, intense laser pulse into the optical fiber and measures the backscatter and reflection of light as a function of time [120]. Rayleigh scattering and Fresnel reflection are physical cause of signal reflection. Backscattered light provides a signature from which information about signal strength is deduced. Interpretation of the OTDR measurement features is aided by knowledge of fiber backscatter and reflection mechanism together with familiarity of the measurement process. The backscattered signal is typically very weak and may suffer from noise-interference. To overcome this problem, the process of sending a pulse and receiving the echo is repeated many times to improve the signal-to-noise ratio through averaging. Pulse width, which is 5ns to 10ns determines the spatial resolution and sensitivity of the measurement.

The concept of return loss is employed to calculate refractive index from the reflected signal obtained from the OTDR. When light is transmitted from medium 1 to medium 2 (e.g. from a fiber to an adhesive), a portion of the incident light is reflected back (Fresnel reflection) into medium 1 due to mismatch in refractive indices (Figure 3.5). The reflection coefficient (RC) is then given by:

$$RC = \frac{(n_1 - n_2)}{(n_1 + n_2)} \quad (1)$$

The percentage of light reflected (R) is as follows:

$$R = RC^2 = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2 \quad (2)$$

Return loss (RL) is then obtained by converting the percentage of light reflected to dB:

$$RL = -10 \log_{10} R \quad (3)$$

Note that a larger return loss number implies a more favorable condition of lower reflected power.

Figure 3.5 Schematic of an optical fiber connector employing an index matching adhesive.

3.4.2 Prism Coupler method

The Prism Coupler is used to explore the dependence of refractive index on annealing temperature. The Prism Coupler is a direct method of measuring refractive index and thickness of a thin film by measuring the angle at which modes can be prism coupled into the film [121]. It employs optical waveguiding techniques to promptly and precisely measure both the thickness and refractive index of films. The output light of the prism coupler source first passes through a prism polarizer with an extinction ratio of 10^{-6} . The polarizer serves two functions: it ensures that the laser output is linearly polarized, and by rotating it, the relative intensities of T_E and T_M modes is adjusted. Each mode leaves the output prism at an angle determined by the effective index within the waveguide. The prism coupler has a higher index accuracy of ± 0.0001 compared to the OTDR, which has an accuracy of only ± 0.001 .

3.4.3. Samples Preparation

Figure 3.6 explains the experimental flow diagram for different characterizations. Samples were prepared in two different ways for the characterization:

3.4.3.2 Temperature study

To investigate the temperature dependence, samples (with fiber) were placed in Teflon insulated temperature chamber which had a temperature uncertainty of 1°C. Schematic of experimental setup is shown in Figure 3.7. The return-loss was measured at a wavelength of 1550nm under different temperatures with OTDR (model AQ7410B). The refractive indices were then calculated from these return loss values (Eq. 1 - 3).

Figure 3.7. Schematic of experimental setup for refractive index measurement with OTDR at different temperatures.

3.4.3.3 Moisture study

To study moisture effect, specimens (with and without fiber) were dry-baked at 70°C for 7 days before being placed in a water beaker at 90°C. Specimens without fiber were removed from the water at fixed time intervals to measure the amount of moisture absorbed. TGA (TA instrument model 2950) was performed on the samples without fiber (after moisture saturation) at a constant temperature (120°C) to determine the moisture desorption data. Using the values of saturated moisture concentration, C_{sat} and the desorption data; the amount of moisture present in the optical adhesive was calculated at different times. The saturated samples (with fiber) were placed on a hot plate (Figure 3.7) at 120°C or 60 °C, to measure the return loss during moisture desorption. The refractive

index of the sample was calculated from the measured return loss values at fixed time intervals.

3.4.3.4 Annealing Study

Spin coated wafer, along with the adhesive, was diced in square shape (2cm × 2cm) and exposed to different annealing conditions as follows:

- (i) The sample was annealed at 60°C for 1 hour.
- (ii) The sample was quenched to room temperature using liquid nitrogen.
- (iii) Steps i and ii were repeated for different temperatures of 70 °C, 80 °C, 90 °C, 100 °C, 200 °C.

The refractive index and birefringence of the diced samples were measured with prism coupler (Metricon model 2010). Finally, thermal DSC and X-ray diffraction (thin film mode) measured crystallinity of the annealed samples. DSC measurements were performed by varying temperature from 0 °C to 250 °C at a heating rate of 10°C/min. XRD was performed in thin film mode from 0 degree to 30 degree.

3.5 Materials Characterization

In order to facilitate the finite element analysis (FEA) of EO transceiver module, a series of experiments were carried out to obtain the values of material properties. Details of each of these experiments have been provided in the following subsections.

3.5.1 Thermo-Mechanical Properties of Optical Adhesives Materials

(a) Thermogravimetric Analysis

TGA was used to investigate the thermal stability of the adhesives by determining their degradation temperatures and detecting possible outgassing during curing. The TGA sample weight used was in the range of 10-20 mg. Samples were ramped between room temperature and 800°C at a heating rate of 10°C/min in nitrogen atmosphere. The change in sample weight at any given temperature during the thermal scan was calculated using the following formulae:

$$\frac{W_T - W_i}{W_i} \times 100\%$$

where W_T is the weight at the given temperature during the scan and W_i is the initial weight before the TGA test.

(b) Dynamic Mechanical Analysis (DMA)

The purpose of the dynamic mechanical experiment is to determine the time and temperature dependent moduli of the adhesive material. The finite element model uses a number of Maxwell elements in parallel to simulate the viscoelastic effect in the material using time dependent modulus (discussed in the next chapter). This experiment determines the parameters needed to represent time and temperature dependent moduli for the adhesive material. To obtain the thermal transition characteristics of the adhesives, DMA experiments were performed using a TA Instruments 2980 dynamic mechanical analyzer (DMA) in 3-cantilever beam mode. To prepare neat DMA samples from uncured adhesives, a rectangular Teflon mold was made. Then, the uncured adhesive was dispensed into the Teflon mold and cured by UV lamp. Finally, the cured sample was machined down to a dimension of 26x5x1.5 mm. In the DMA studies, the samples were tested at a heating rate of 5°C/min from 30°C to 200°C with a single oscillation frequency of 1Hz. Single frequency results are useful for elastic FEA modeling. Same samples were run through multifrequency analyses to determine the viscoelastic parameters of the adhesive.

(c) Thermomechanical Analysis

A TA 2940 Instruments thermomechanical analyzer (TMA) was used to measure the expansion as a function of temperature and yield information of the linear thermal expansion coefficient (CTE) of the optical adhesive. TMA samples were prepared in rectangular Teflon mold. The cured sample was machined down to a 5x5x1.5 size rectangle. In the TMA studies, the samples were tested at a heating rate of 5°C/min from 30°C to 200°C.

(d) Time-Temperature Superposition (TTS)

Polymeric materials are viscoelastic solids; hence their properties are both temperature and time dependent. Since most of the reliability tests are conducted for prolonged durations, time-temperature-superposition (TTS) technique is used to obtain the master curve of each material at that required temperature. This helps to characterize the stress relaxation or drop in storage modulus over long time durations.

TTS experiments were conducted on the TA Instruments 2980 DMA using multifrequency mode on a film tension clamp. Figure 3.8 shows the DMA multiplex method used for TTS experiments. The sample temperature was increased from 30°C to 250°C, in steps of 5°C. At each temperature step, an isothermal soak time of 5 min was applied to ensure uniform temperature distribution within the sample. The sample was then swept through multiple frequencies from 60 Hz to 0.1 Hz, before stepping on to the next temperature.

Figure 3.8 DMA multiplex method for TTS experiment

3.6. Optical output measurements

3.6.1 Fiber-to-fiber optical coupling

Fiber-to-fiber alignment was studied in order to quantify the impact of fiber attachment process on the transceiver coupling efficiency. Two well-cleaved fibers were attached in one V-groove and an external laser power source (Thorlabs), operating at 1510 nm with 1mW power output, and a power meter (Newport-2832C) were used for measuring optical coupling efficiency. Connector loss, attenuation loss, reflection loss and other losses were calculated separately to determine the misalignment loss from total loss.

Optical loss due to improper cleaving of fiber and reflection loss along with connector and attenuation loss were found by measuring the output without attaching the fiber with adhesive. Finally, coupling loss is measured after curing of the adhesive, which completes the analysis of the loss due to misalignment of fiber during the curing process.

$$P_1 = P_0 - \text{output power (fiber is joined to light source and power meter without cutting the fiber)} \quad (6)$$

$$P_2 = P_0 - (P_1 + \text{output power without addition of adhesive}) \quad (7)$$

$$P_3 = P_0 - (P_1 + P_2 + \text{Output power after curing of adhesive}) \quad (8)$$

Where, P_0 , P_1 , P_2 and P_3 are input power, power loss due to connector, power loss due reflection and improper cleaving of fiber, and coupling loss due to misalignment, respectively.

$$\eta(\%) = \frac{\text{OutPower(mW)}}{\text{InputPower(mW)}} \times 100 \quad (9)$$

3.6.2 Test vehicle output measurement

Assembled optical module on the SiOB was fired by keeping the laser diode output power constant to 1mW. A large area detector (in constant current mode) was kept in front of the single mode optical fiber to monitor the total output optical power coming from the fiber. The distance between the detector and the optical fiber was minimized (<0.1mm) to avoid any optical loss after the fiber.

Optical adhesive was placed between the optical fiber and laser diode to enhance the coupling efficiency. The optical output was measured after filling the optical adhesive between the LD and SMF.

3.7 Experiment for Reliability study of the optical module

Optical alignment of laser diode-to-optical fiber was examined in thermal cycle conditions. Thermal cycle test conditions used are in compliance with the Telcordia-GR-1221-CORE standards. GR-1221-Core states that the qualification depends upon

maintaining optical integrity throughout an appropriate test regimen. In this reliability study of the optical alignment, the temperature is varied between 85°C and -40°C with 5 minute ramps and 15 minute holds. The ramp rate is 25°C/min. 30 assembled test vehicles were kept in the temperature cycle chamber for 100 cycles. Samples were taken out after 100 cycles and optical output was measured.

4. Materials Property Characterization of Optical Adhesive

In recent times, acrylate based optical adhesives are being increasingly used in the packaging and assembly of optical communication modules [24, 122-124]. Optical adhesives perform dual functions of physically attaching the components and of minimizing the reflection loss in optical path. These adhesives are advantageous due to their low cost and amenability to mass production. Adhesives designed for use in the optical path typically offer a very high clarity (transparency of >90%) and come with a wide refractive index range (1.40-1.70) [122]. They are used between light passing sections to minimize the reflection losses (Fresnel reflection) in packages [122, 24]. When light is incident on the interface between two mediums, part of it is reflected away from the interface and rest is transmitted into the new medium. The fraction of the incident light amplitude that is reflected can be calculated using the Fresnel equation:

$$R = \left[\frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \right]^2 \quad (1)$$

The ratio (in dB) of optical power arriving at the interface to the optical power reflected back from the same interface is defined as optical return loss (ORL). According to Telcordia standards, the return loss requirement for planar lightwave circuits (PLCs) is 40dB (GR-1209). The ORL at air ($n \approx 1.0$) and single mode optical fiber core ($n \approx 1.468$) interface is approximately 14.7 Db according to the equation 1. Thus, optical adhesives are filled in the air gap to minimize the refractive index mismatch.

The optical adhesive used for this research has a refractive index of 1.463, which makes the reflection loss almost zero at the fiber interface (detail description of adhesive in chapter 3). Optical adhesives or index matching materials are made of polymer materials, which are transparent in nature. Generally it is observed in the case of polymer materials that they are very sensitive to the environment conditions. In the present chapter, the refractive index of the UV- curable optical adhesive is characterized for varied environmental conditions, like temperature, humidity and annealing. Optical time domain reflectometry (OTDR) and prism coupling methods were employed to measure optical properties of the adhesive. Effect of temperature, humidity and annealing on the

refractive index of the optical adhesive is discussed in section 4.1. Details of these equipments and the measurement method are described in the experiment chapter.

The optical adhesive is used for physically attaching the optical fiber to the V-groove. Optical adhesive's thermo-mechanical properties were determined to analyze the shift of the optical fiber due to thermal treatment. Finite element analysis and experimental method were employed to study the fiber shift and results have been discussed in the next chapter. The thermo-mechanical properties of the adhesive were studied using DMA (modulus), and TMA (coefficient of thermal expansion) measurements and the result is presented in section 4.2. Viscoelastic property characterization of the adhesive is important because it helps in understanding the long term behavior of the optical adhesive-fiber joint. It is also discussed in section 4.2.

4.1 Effect of environmental conditions on the refractive index of the optical adhesive

4.1.1 Dependence of refractive index on temperature

Figures 4.1a and c show refractive index (n) of optical adhesive and $\tan \delta$ (DMA) against temperature. These plots show that n decreases with increase in temperature. The refractive index measured at 25°C was 1.463 for $\lambda = 1550$ nm, in agreement with the data

(c)

Figure 4.1 (a) Temperature (in ° Centigrade) dependence of refractive index. (b) Variation of dn/dT vs. temperature (b) $\tan\delta$ (DMA) graph for optical adhesive sheet values for the adhesive materials. The calculated thermo-optic (TO) coefficient (dn/dT) is plotted in figure 4.1b. In a temperature range of 20-70 °C the thermo-optic coefficient is almost constant with a value of $-1.8 \times 10^{-4}/^{\circ}\text{C}$, and changes drastically to a lower value $-4.2 \times 10^{-4}/^{\circ}\text{C}$ in the 75-120 °C range. In order to understand the drastic changes in the thermo-optic coefficient between 70°C and 75°C temperature range, DMA measurements were performed to investigate the glass transition temperature of the adhesive. The $\tan \delta$ curve for the adhesive is shown in Figure 4.1 (c). The $\tan \delta$ graph shows a peak at $\sim 78^{\circ}\text{C}$ corresponding to the glass transition temperature. This glass transition temperature ($T_g \sim 78^{\circ}\text{C}$) of the adhesive is in the same range as the observed discontinuity in the TO coefficient between 70°C and 75°C temperatures.

The drastic change of thermo-optic coefficient around the glass transition temperature suggests that the change of refractive index may have a relationship with density [90]. Moreover, according to Lorentz-Lorenz law, refractive index is related to density by the following equation:

$$(n^2-1) / (n^2+2) = \rho RD/M \quad (2)$$

where RD is molar refraction, M is molecular weight and ρ is the density of material. Molar refraction and molecular weight remain nearly constant with changes in temperature and pressure. Changes in refractive index occur by virtue of the density factor, which is a function of temperature and pressure. This relationship is consistent with the results obtained; as temperature increases, the adhesive refractive index

decreases because of increase in volume due to its high coefficient of thermal expansion ($75 \times 10^{-6} / ^\circ\text{C}$), as measured by TMA, and thus resulting in lowering of density.

4.1.2 Dependence of refractive index on moisture content

Refractive index and moisture content of the adhesive as determined by the return loss and TGA respectively, at 60°C and 120°C are presented in Figure 4.2. Refractive index increases at a gradual rate of $2 \times 10^{-6} (\% \text{ moisture})^{-1}$ and $7 \times 10^{-6} (\% \text{ moisture})^{-1}$ for 60°C and 120°C respectively. The relationship between humidity and refractive index of the polymer can be derived from the Lorenz-Lorenz equation [87]:

$$\frac{dn}{dH} = \frac{(n^2 + 2)^2}{6n} k_m S \left(1 - \frac{f}{f_c} \right) \quad (3)$$

where S is the moisture solubility of the polymer, and k_m is molar refraction divided by the molecular weight. f is the fraction of the absorbed moisture that contributes to an increase in polymer volume, which is a function of temperature, and f_c is critical value of f . The volume change for the PMMA was found to be half of the change in weight due to the water absorption [125]. It was assumed that microvoids contribute mainly to the reduction of volume change. Moisture get settled in the free space which available in the form of microvoids. Thus, the volume change of the polymer materials is not directly proportional to the moisture sorption in starting. As the microvoids are completely fi-

lled then moisture contribute to the volume change directly and its volume add to the polymer volume. In the case of fluorinated polyimide, it has been suggested that the small volume change (low f value) is due to the loose intermolecular packaging structure [126]. When f becomes larger than f_c , refractive index decreases with increase in moisture uptake because swelling occurs largely at higher temperature. In the case of PMMA for the temperature $>60^\circ\text{C}$, f becomes greater than f_c , thus n started decreasing with moisture absorbed¹¹. f factor at 120°C is greater than its critical value, thus refractive index increases more sharply with decrease in moisture content as compared to 60°C (Figure 4.2b). The coefficient of thermal expansion of the adhesive is comparatively high due to which f value becomes greater than f_c at 120°C . There is no significant change in refractive index with moisture desorption at 60°C . A similar trend for refractive variation with moisture absorption was found in the case of d-PMMA [87].

A permanent change in the value of refractive index was observed due to moisture absorption (Figure 4.1a and Figure 4.2b), which was more significant at 120°C . It may have occurred due to irreversible chemical change in the adhesive during the moisture absorption. In the case of PMMA, it was observed that at higher temperature, moisture can react with ester group to form methanol [127]. A more detailed study of the chemistry of moisture reaction with adhesive molecules is required for an in depth explanation of this phenomenon.

4.1.3 Dependence of refractive index on annealing

The refractive indices of the optical adhesive were obtained by using the prism coupler at different annealing temperatures, as shown in Figure 4.3a. The TE mode of the prism co-

Figure 4.3. Relationship between annealed temperature, refractive index and birefringence for both T_E and T_M modes for constant annealing time of 1 hour

upler measures the refractive index of the adhesive for electric field which vibrates parallel to the material surface. On the other hand, the TM mode measures the index for electric field vibrating perpendicular to the material surface. In both the TE and TM modes, refractive index was observed to increase with increase in annealing temperature.

This increase in refractive index was attributed to change in density of material as per Lorentz-Lorenz law. Density changes due to physical aging and the process of molecular orientation, leading to an increase in crystallinity. Physical aging is a time and temperature dependent phenomena, which results in volume relaxation leading to increase in material's density [121]. Volume relaxation of acrylate based polymer due to annealing was determined by measuring the change in refractive index of the material. Thermal DSC (for short-range order [87, 127]) and XRD (for long-range order) results rule out the possibility that refractive index could have increased due to crystallinity change (Figures 4.4, and Figure 4.5). The amount of heat absorbed ($-\Delta H$) in the annealed sample was measured using the DSC data (Figure 4.4). The amount of residual crystallinity present in the adhesive after annealing was calculated with the help of $-\Delta H$. Residual crystallinity increases with increase in annealing temperature; thus the amount of short-range crystallinity present in the samples decreases with increase in annealing temperature. Optical adhesive gets more and more amorphous with higher annealing temperatures.

Figure 4.4. Thermal DSC of samples annealed for 1 hour at different temperatures. The trough areas of the thermal DSC correspond to the heat because of the change in short range crystallinity, which increases with increase in annealing temperature.

Figure 4.5. XRD of optical adhesive annealed at different temperatures.

Similarly, XRD result (Figure 4.5) does not show any sign of change in long-range crystallinity in the adhesive. Thus, overall crystallinity gets decreased due to annealing and as a result, density goes down. Another cause for increase in refractive index could be incomplete curing during sample preparation. This might get compensated during the annealing process of samples. UV-DSC plot of heat flow for raw and cured material is presented in the Figure 4.6. The raw sample gave off a large amount of heat during the

Figure 4.6. UV-DSC plots for uncured and cured adhesive samples. Only the raw material is showing the heat flow change and cured samples don't show any change in heat flow

curing process as indicated by the trough (Figure 4.6). However, there is no such trough observed for cured samples, which suggests that no reaction occurred during the entire UV exposure (Figure 4.6). Thus, it can be concluded that all samples were completely cured during sample preparation. It can also be concluded that the variation in refractive index with annealing temperatures was not due to residual curing processes. Therefore, changes in refractive index due to annealing results from the adhesive volume relaxation.

Figure 4.3a shows the variation of birefringence with annealing temperature, as measured by a prism coupler. Birefringence was calculated from the difference in refractive index between the TE and TM modes (plotted in Figure 4.3b). The adhesive film has a temperature-dependent birefringence ($\Delta(n_{TE} - n_{TM}) / \Delta T$) of $1.86 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$. The relation between polarization and temperature is largely linear. Anisotropy in the optical property of adhesive is determined by the chemical configuration and conformation of a polymer chain. Birefringence of a material provides information about the crystallinity and orientation of the polymer molecular chains. As depicted in Figure 4.3b, the birefringence of the adhesive decreases with increase in annealing temperature. This

means that optical adhesive has become more isotropic due to the heat treatment as shown by decrease in short-range crystallinity (Figure 4.5) observed by the thermal DSC.

The presence of residual stresses also results in distortion of molecular chain and induces birefringence in the polymeric materials. The curing process of the adhesive causes residual or internal stresses which relax with time during the annealing. Decrease in the birefringence can take place due to the stress relaxation in adhesive film as well. The subsequent slow progression of the polymer towards equilibrium, termed structural recovery, takes place during annealing process and helps in reducing the birefringence of the adhesive material.

4.2 Thermo-mechanical properties of optical adhesive

4.2.1 Coefficient of thermal expansion (CTE)

The TMA was used to obtain the coefficient of thermal expansion (CTE), which is the amount of expansion per unit change in temperature. Figure 4.7 shows TMA curve obtained for the optical adhesive. Analysis of CTE was done by determining the slope of the dimensional change versus temperature. Generally polymers show sudden change in the thermal expansion rate at the glass transition temperature (T_g). Similarly, optical adhesive shows two CTE values, CTE 1 ($151.2 \times 10^{-6} / ^\circ\text{C}$) and CTE 2 ($217.5 \times 10^{-6} / ^\circ\text{C}$) for temperatures below and above T_g respectively. In some cases, T_g of polymer is also determined by the onset point between the two slopes of thermal expansion.

Figure 4.7. TMA of the optical adhesive

4.2.2 Modulus of the adhesive materials

To obtain the storage modulus at various temperatures, dynamic mechanical analysis (DMA) was conducted on cured optical adhesive samples. The DMA experiment was performed on the TA Instruments 2980 DMA in film tension mode by ramping at $5^\circ\text{C}/\text{min}$ from room temperature to 250°C under a frequency of 1 Hz and amplitude of $15 \mu\text{m}$. Figure 4.8 shows a DMA curve obtained, showing the storage modulus (E') against temperature for the optical adhesive. The storage modulus represents the elastic nature of the sample. This observation has been incorporated in thermo-mechanical elastic modeling of the optical module. It is to be noted that the modulus manifested a monotonous decrease with the rise in temperature, whereas the data input in the FEA of the test vehicle were assumed to decrease step wise.

Figure 4.8. Variation of modulus of the optical adhesive with temperature

4.2.3 Viscoelastic property of the optical adhesive

Adhesive materials, because of their viscoelastic nature, exhibit deformation and flow; this behavior is dependent on both temperature and time. For example, if the adhesive is subjected to a constant load, the deformation exhibited by the material will increase over a period of time. This occurs because the adhesive material under a load undergoes molecular rearrangement in an attempt to minimize localized stresses. Hence, modulus measurements performed over a short time span yield lower values whereas those performed over a longer time result into higher values. This time-dependent behavior would seem to imply that the only way to accurately evaluate material performance of a specific application is to test the material under the same temperature and time conditions the material shall experience during the application. This implication, if true, would present real difficulties because the range of temperatures and/or time covered by a specific instrument might not be adequate, or at best might result in extremely long and tedious experiments. Fortunately, however, there exists a treatment of the data, designated as the method of reduced variables or time-temperature superposition (TTS), which overcomes the difficulty of extrapolating limited laboratory tests at shorter times to longer term, more real-world conditions.

The underlying bases for time/temperature superimposing are (1) that the processes involved in molecular relaxation or rearrangements in viscoelastic materials occur at accelerated rates at higher temperatures and (2) that there is a direct equivalency between time (the frequency of measurement) and temperature. The time-span over which these processes occur can be reduced by conducting the measurement at elevated temperatures and transposing (shifting) the resultant data to lower temperatures. The result of this shifting is a “master curve” where the material property of interest at a specific end-use temperature can be predicted over a broad time scale. The amount of shifting along the horizontal (x-axis) in a TTS plot required to align the individual experimental data points into the master curve is generally described using the Williams-Landel-Ferry (WLF) equation [128]:

$$\log A_t = \frac{-C_1(T - T_o)}{C_2 + (T - T_o)} \quad (4)$$

where C_1 and C_2 are constants, T_0 is the reference temperature (in K), T is the measurement temperature (in K), and A_t is the shift factor. The WLF equation is typically used to describe the time/temperature behavior of polymers in the glass transition region. The equation is based on the assumption that, above the glass transition temperature, the fractional free volume increases linearly with increase in temperature. The model also assumes that as the free volume of the material increases, its viscosity rapidly decreases.

Figure 4.9 shows the G' curves obtained for optical adhesive as a function of temperature at several frequencies. Figure 4.10 shows the resultant master curves after shifting the initial curves to a reference temperature of 343 K (70°C) using the WLF model. Figure 4.11 shows plot of the shift factors expected for the WLF model (solid lines) versus the actual shift factors obtained from the automatic curve-fitting routine in the software (open square). The shift factors obtained for the model exhibit a good agreement with theory, indicating that the model can be used to predict behavior for optical adhesive within this temperature region. Figure 4.10 summarizes the key constants derived from these plots. If the agreement between the theoretical shift factors and those obtained from automatic shifting is not satisfactory, the operator has the option to manually adjust the

shift factors in Figures 4.11 to agree completely with theory and generate a new master curve. In this study, this process is not necessary as the values correlate. Comparing the original G' results in Figure 4.9 to the master curves in Figures 4.10, it is easy to see that the TTS treatment in this material has increased the range for predicting modulus change versus time (frequency) by at least two decades from the range covered just by the raw experimental data.

Figure 4.9. Multifrequency storage modulus curve for the optical adhesive

Figure 4.10. Master Curve at 70°C. C1 and C2 constant of TTS WLF model.

Figure 4.11. WLF shift factors

5. Fiber Misalignment Determination: FEA and Experiments

In this chapter, the effect of attachment process parameters (such as the amount of bulk adhesive, and the thickness/symmetry of the adhesive layer between the fiber and V-groove walls) on the alignment of the fiber with the laser diode assembled on SiOB is studied. Finite Element Analytical (FEA) models for determining displacement and strain in optical modules aid the understanding of failure mechanism and factors that affect its lifetime. The framework of a model that incorporates elastic and viscoelastic properties of the adhesive is presented here. The presence of stress concentration points and localized nature of failures make the finite element model a logical choice for determining the displacement / strain in an optical module. The primary use of this finite element model is to calculate the plastic work accumulated in the adhesive joints during the thermal cycling so that some existing method of predicting long-term misalignment can be used. Some observations about stress distribution during thermal cycling are also given here. Validation of the FEA data was accomplished by the use of in-situ Micro Moiré interferometry (MMI). MMI determines the displacement of the centre of the fiber in the V-groove when the groove is exposed to a temperature excursion ranging from room temperature to 125°C.

Section 5.1 gives an overview of the finite element model. Section 5.2 presents the details of the model development, focusing on the geometry, materials properties, and loading conditions. Section 5.3 present the results of both elastic and viscoelastic simulations. Elastic model results are compared with the experimental results of MMI in subsection 5.3.2 and 5.3.3. The experimental setup and details for MMI has been described in the chapter 3.

5.1 FEA Overview

Finite element analysis of the structural model of optical module has been carried out in two steps. In the first step, the mechanical stress / displacement incurred is studied by considering the elastic properties of materials and verifying the developed FEA model using experiments. FEA model was verified against the experimental result of the optical

fiber displacement measured by the moiré interferometry. Then, using the same structural model in the second step, the displacement of the optical fiber for thermal cycle loading is calculated by taking the viscoelastic property in account. This part focuses on the study of the displacement / strain in the optical module accumulated during the high temperature loading and thermal cycling. This portion of analysis predicts the optical failure of optical modules due to temperature changes. It also includes the effect of different parameters on adhesive residual stresses and optical fiber displacement, which could be deleterious to fiber-adhesive joint strength on SiOB and may lead to the failure of optical modules. There are many factors involved in the adhesive-fiber joints such as the design of assembly platform, the amount of adhesive used and the properties of the adhesive material. These factors may be responsible for the fiber shift under temperature cycling. Furthermore, the order of the fiber shift is quite small, in the range of sub micrometer. It is difficult to measure a submicron level shift in the fiber during thermal loading. Thus, structural finite element method can help in identifying the dominant factors contributing to the fiber shift during thermal loading.

A two-dimensional plane strain model of the laser diode to fiber alignment on the SiOB was chosen for analysis. Two-dimensional models have been shown to sufficiently capture the influence of optical design parameters on fiber-solder joint stress [99]. ANSYS[®]6.1, a general purpose finite element program, was used to generate the model, solve the stress / displacement problem, and analyze the results. Although this is a time dependent problem, a quasi-static analysis at successive time steps is used. The loads are assumed to be applied slowly during each step. Mass inertia effects are not included for simplicity. The basic equation solved for each step is given as:

$$[K]\{u\} = \{F\}, \quad (1)$$

Where $[K]$ is the stiffness matrix, $\{u\}$ is the displacement vector, and $\{F\}$ is load vector.

5.2 FEA Model Development

5.2.1 Geometry

Figure 5.1a shows a configuration of the 2-D mechanical model of optical module established by the ANSYS software. Figure 4b is a close up of the element configuration

around the optical fiber. The mesh density is designed to be greater in area of higher stress gradient namely the fiber adhesive joint. The FEA model consists of more than 7,000 nodes and the mesh in the neighborhood of the fiber-adhesive joint is refined in order to achieve sufficient accuracy in the calculation. Dimension of the structure used in the model is shown in Figure 5.1b. The dimensions were taken from the specimens used in the validation experiment.

Figure 5.1 (a) A representative FEA model of the fiber-adhesive joint, with the fiber in the V-groove center. (b) Model is meshed with plane 13 element of ANSYS and region around the silicon-adhesive-fiber attachment is very fine meshed.

The boundary conditions are illustrated in figure 5.1a. The lower left corner was fixed and the bottom horizontal line of silicon optical bench was prevented from Y-axis movement. Perfect bonding was assumed for all material interfaces. Symmetry boundary condition about the fiber center (in Y-Z plane) was not considered in the analysis because fiber is not necessarily in the exact center of the V-groove. The effect of different positions of the fiber in the V-groove on the final fiber displacement is studied in detail.

5.2.2 Material Properties

5.2.2.1 Optical fiber and Substrate

The four node thermal-mechanical coupled element (PLANE13) was used in this direct couple field analysis. The silicon substrate and fiber materials properties used in this analysis were taken from reference [99] and are listed in table 1.

5.2.2.2 Optical Adhesive

The four node thermal-mechanical coupled element (PLANE 13 for elastic analysis and VISCO 88 for viscoelastic analysis) was used in the direct couple field analysis. Optical adhesive property for the elastic modeling is mentioned in the table 5.1.

Table 5.1 Thermo-mechanical properties of fiber-adhesive joint materials. SMF and Si properties are as reported in reference 4.

	Young Modulus (N/μm ²)	CTE 10-6 (°C)
Single Mode Fiber (SMF)	0.08	0.56
Silicon (Si)	0.137	3.8
Adhesive (-40°C)	0.0012	60
Adhesive (100°C)	0.0010	120
Adhesive (150°C)	0.0007	120

The viscoelastic effect is incorporated using the materials properties of the element. The ANSYS viscoelastic element VISCO 88 is used to represent the optical adhesive. In the context of small strain theory, the constitutive equation for an isotropic viscoelastic material can be written as:

$$\sigma = \int_0^t 2G(t-\tau) \frac{de}{d\tau} d\tau + I \int_0^t 2K(t-\tau) \frac{d\Delta}{d\tau} d\tau \tag{2}$$

Where:

σ = Cauchy stress

e = deviatoric part of the strain

Δ = volumetric part of the strain

G(t) = shear relaxation kernel function

K(t) = bulk relaxation kernel function

t = current time

τ = past time

I = unit tensor

For the viscoelastic elements VISCO 88, the optical adhesive properties is expressed in integral form using the kernel function of the generalized Maxwell elements. The kernel functions are represented in terms of Prony series, which assumes that:

$$G = G_{\infty} + \sum_{i=1}^{n_G} G_i \exp\left(-\frac{t}{\tau_i^G}\right) \quad (3)$$

$$K = K_{\infty} + \sum_{i=1}^{n_K} K_i \exp\left(-\frac{t}{\tau_i^K}\right) \quad (4)$$

In the above, G_{∞} and G_i are shear elastic moduli, K_{∞} and K_i are bulk elastic moduli and τ_i^G and τ_i^K are the relaxation times for each Prony component. n is the number of Maxwell element considered for the analysis, which is seven for this study. Numbers of Maxwell element decide the accuracy of the result and time required for the analysis.

Introducing the relative moduli

$$\alpha_i^G = G_i / G_0 \quad (5)$$

$$\alpha_i^K = K_i / K_0 \quad (6)$$

Where:

$$G_0 = G_{\infty} + \sum_{i=1}^{n_G} G_i \quad (7)$$

$$K_0 = K_{\infty} + \sum_{i=1}^{n_K} K_i \quad (8)$$

The integral function Eq.2 can compute the elastic behavior even at the limits of very slow and very fast load. Here, G_0 and K_0 are, respectively, the shear and bulk moduli at the fast load limit (i.e. the instantaneous moduli), and G_{∞} and K_{∞} are the moduli at the slow limit. The elasticity parameters being input correspond to those of the fast load limit. Moreover by inserting Eq.3, the deviatoric and volumetric parts of the stress are assumed to follow different relaxation behavior. The number of Prony terms for shear n_G and for volumetric behavior n_K need not be the same nor do the relaxation times τ_i^G and τ_i^K . Effect of bulk modulus is not considered in this analysis because of insignificant effect produced by the bulk modulus compare to the uniaxial and shear moduli at long time or high temperatures. Also, experimental characterization of viscoelastic material is performed by combining measurements of the uniaxial or shear relaxation moduli with the assumption that the either bulk modulus or Poisson ration remains constant. An

assumption that the Poisson ratio remains constant is considered for this study to ease the calculation of algebraic expression used to describe the viscoelastic behavior of optical adhesive.

5.2.2.2.1 Determination of Prony series

The Prony series coefficients and retardation times appearing in Equation 3 and 4 need to be determined in a regression analysis. Here, a standard nonlinear regression method (the Marquardt-Levenberg Method [129]) is used for data fitting. In the nonlinear regression, an error function (χ^2) with respect to the unknown constants is defined as:

$$\chi^2(a) = \sum_{i=1}^N \left[\frac{y_i - y(x_i; a)}{\sigma_i} \right]^2 \quad (9)$$

where x_i and y_i are the experimental data, function $y(x_i; a)$ is the model to be fitted, and σ_i is the standard deviation of measurement error of i -th data point. A set of unknown constants (a) will be determined that minimize the error function χ^2 . The error function (χ^2) is approximated by its Taylor series with the quadratic form:

$$\chi^2(a) = c - d \cdot a + \frac{1}{2} \cdot a \cdot D \cdot a \quad (10)$$

where c is a constant and d is the gradient of χ^2 with respect to the parameter a , which will be zero when χ^2 is minimum. Matrix D is the second partial derivative of χ^2 with respect to the parameter a . Initial trial values of α are specified and improved values are determined by the nonlinear regression algorithm. This step is iterated until the error function, χ^2 , effectively stops decreasing.

Since each Prony term includes two variables (G_i and τ_i) and since the instantaneous modulus (G_∞) must be determined, the total number of variables in the regression is $2n+1$. Based on thermodynamic principles, several constraint conditions must be applied:

$$G_i \geq 0, \sum G_i \leq 1, \tau_i \geq 0, G_\infty > 0 \quad (11)$$

In addition, the distribution of the standard deviation of measurement error (σ) is not easily determined. This distribution is based on the error of data acquisition equipment and the error of test machine, and is usually assumed to be uniform for all data points (σ_i

= 1). As is well known, the viscoelastic effects are most significant at the beginning of the relaxation period; hence the fitting error in this region should be minimal. Since the percentage of the number of data points at the beginning of the relaxation period is less, the error function χ^2 is dominated by a long uniform tail region of the relaxation period. To reduce the error and improve the fit at the beginning of relaxation period, a weight function ($w = 1/\sigma$, $0 < \sigma < 1$) is used. The larger the weight factor at a data point, the better the curve fits the point. As there is no analytical method to determine the weight function, it is determined by trial-and-error. The acceptance of the weight function is based on a graph of data and regression model results. Weighted nonlinear regression requires more iterations than unweighted nonlinear regression, but it can provide a better fit to the experimental data in the relevant region.

The Marquardt-Levenberg nonlinear regression method was applied by the commercial software Origin to obtain the Prony series coefficients for the optical adhesive shear modulus data (which is mentioned in form of master curve in the last chapter). Weight function should be selected based on the material properties and test data distribution. Properly selecting the weight function (Table 5.2) in the most significant region improves accuracy of the regression. The Prony constants of the regression are shown in Table 5.3.

Table 5.2. Weighted function for Marquardt-Levenberg nonlinear regression

w1	w2	w3	w4	w5	w6	w7
16.48	2.43	2.95	6.44	35.91	336.88	571.29

Table 5.3. The Prony constants for the regression

	1	2	3	4	5	6	7
G _i	6.07e7	4.123e8	3.391e8	1.554e8	2.79e7	3.00e6	1.80e6
τ _i	3.2e-8	2.6e-6	2.14e-4	0.018	1.507	124.45	10400

Prony constants for different Maxwell elements (3, 5, and 6) were also determined. 7 Maxwell elements were chosen to simulate the viscoelastic effect as it gave the best fit for the curve.

5.2.3 Load Step

5.2.3.1 Temperature loading (elastic model)

The first step of finite element modeling was to understand the effect of adhesive thickness between the fiber and inclined V-groove wall (discussed in next subsection), and the adhesive amount on the thermal induced displacement of the fiber. Of primary interest here is the sensitivity of the resulting alignment shift in the fiber resulting due to the variation in adhesive thickness between the fibers and V-groove walls. The temperature is varied from -40°C to $+85^{\circ}\text{C}$ (Telcordia standard: GR1221), and the fiber displacement induced by the temperature variation is determined using the elastic properties of adhesive materials.

5.2.3.2 Thermal Cycling model

The loading in the thermal cycling model simulates hundred temperature cycles, each of forty minutes (shown in Figure 5.2). The temperature is cycled between 85°C and -40°C with 5 minute ramp and 15 minutes holds. The ramp rate is $25^{\circ}\text{C}/\text{min}$. A time step size of 1 is used throughout the simulation. This procedure is generally based on Method 1010.7 of MILSTD- 883E. The simulation is performed to predetermine resistance of a part to extreme temperatures, both hot and cold, as well as to determine the effect of alternate exposures to these extremes. The purpose of temperature cycling is to investigate the stability of an optical alignment by changing alternatively between cold and hot temperature. The difference in thermal expansion coefficient arises from the stacks of optical components, and attaching materials. These factors cause optical misalignments which change the output power of fiber; thereby degrading the optical module. The key parameters of the simulation are cold and hot temperature, transfer time, and dwell time. The cold and hot temperature is set to -40°C and 85°C , respectively. The hot temperature of 85°C is higher than that shown in Telcordia GR-468-CORE due to the requirement of DWDMsystem vendors. The maximum transfer time from hot to cold or cold to hot is

relaxed from the standard time of less than 1 min to a minimum temperature ramp rate of 25°C/min. An optical module’s pass/failure status is determined by the test results; 100 cycles for use in central office (CO) environments, and up to 500 cycles for informational purposes only.

Figure 5.2 Temperature cycle for thermal loading

5.3 Fiber -Adhesive Joint in V-groove

The fiber-adhesive joint in the silicon V-groove of the laser module is shown in Figure 5.3a. The final position of the fiber depends on the how the fiber is held during attachment, the curing conditions, and the adhesive material’s properties. Three different possible positions of the fiber in the V-groove after the adhesive curing are shown in Figure 5.4: (A) the optical fiber is in contact with both the inclined walls of the V-groove (Figure 5.3b), (B) the optical fiber does not touch either of the inclined walls (Figure 5.3c), and (C) the fiber touches one of the inclined walls (Figure 5.3d). The fiber can remain in contact with the V-groove walls if high pressure is applied throughout the

Figure 5.3 (a) Schematic of laser diode to single mode fiber alignment on silicon optical bench. Different possible situation of fiber-adhesive joint in V-groove (b) fiber in direct contact with inclined walls, (c) fiber not in contact with wall but in symmetry position, and (d) unsymmetrical position of fiber. (e) Different forces acting on the fiber at the time of curing process of adhesive. Note that the adhesive layer thickness between the fiber and V-grooves wall gap is shown in Figure 5.3c and 5.3d.

Figure 5.4 SEM picture of fiber-adhesive joint in V-groove for moiré interferometry joint of (a) Sample 1 and (b) Sample 2.

adhesive curing process. An intentional spacing between the fiber and the walls can be introduced for better alignment and to minimize the residual stress around the fiber, or for physical reasons. For example:

1. Generally, the laser diode chips have a dimensional uncertainty of more than $\pm 10\mu\text{m}$ in the height plane and $\pm 2\mu\text{m}$ for the active area with respect to upper surface. This is one of the main barriers in adopting passive alignment in optical module assembly. In some modules, during active alignment, the fiber is placed at a fixed distance from the V-groove walls to compensate for laser dimension uncertainty.
2. Internal stresses exist within the optical adhesives wherever chain segments are under tension or compression. Mainly, the stresses arise during the curing process of the adhesives. They are often located at regions where parts of molecules are unequally attracted by its' neighbors. Such unequal attraction can occur at the point of direct contact of the fiber and V-groove wall in the fiber-adhesive joint. Residual stresses can occur when the crosslink density within the adhesive varies markedly from one location to another. These stresses which arise during curing or when in use, can lead to failure of the adhesive because they may initiate cracks. Stress distribution studies for solder and fiber joint on silicon substrate shows that a very high stress is developed underneath the fiber in the solder compared to the outer region [99]. It was also found that shear strain increases significantly in the solder when the spacing between the fiber and substrate is decreased. Thus, a continuous adhesive layer between the fiber and silicon wall is important to achieve mechanical stability.
3. Optical adhesives may get trapped between the V-groove walls and the fiber due to lack of appropriate pressure during placement, excess volume, and material shrinkage during the attachment process. In Figure 1e, different forces acting during the attachment process are shown. The fiber size is quite small (diameter $125\mu\text{m}$, and length few millimeters), and therefore, before the adhesive is cured, its buoyancy forces dominate over body forces of the fiber. Throughout the curing process, shrinkage of the adhesive can compel the fiber to separate itself from the inclined walls. Another factor is irregular surface (roughness) of V-groove wall and the low viscosity of the optical adhesives, which causes sliding of the adhesive

during dispensing. Based on the three-point contact principal, by applying pressure on the top of the fiber, misalignment due to curing shrinkage can be ruled out. But, this will also introduce inhomogeneous stress in the joint, as discussed earlier.

The gap between the fiber and the inclined V-groove wall is quantified with the help of adhesive thicknesses. The adhesive thickness between the fiber and V-groove wall, shown in Figure 5.1c, is defined as the shortest gap perpendicular to the inclined wall

5.4 Results

5.4.1. Elastic modeling Results

Figure 5.5a shows the Y-displacement of the fiber center with respect to the temperature for different adhesive thicknesses. It has been assumed that the fiber center is perfectly aligned with respect to the laser diode at room temperature (23°C) and the adhesive layer thickness on both sides of the inclined walls is equal. The X-displacement is found to be zero because of the symmetrical position of the fiber in the V-groove. The displacement of the fiber center is due to the adhesive expansion during a change in the temperature. The effect of silicon and fiber expansion is negligible because of the low CTE of these materials (Table 5.1). In Figure 5.5b, the Y-displacement of the fiber center for various adhesive thicknesses is plotted as a function of the temperature. The displacement of the fiber varies linearly with respect to the layer thickness. For an adhesive thickness of 8 μm the fiber center is displaced by 1.1 μm , sufficient to cause significant coupling loss for a single mode optical module [7, 130].

The thickness of optical adhesive, between fiber and the inclined groove walls, may be non-uniform due to various factors: mechanical problems, manual attachment process and adhesive shrinkage. The effect of non-uniformity of the adhesive thickness on the fiber displacement is also simulated by means of the same FEA model. Figure 5.5 shows

(a)

(b)

Figure 5.5(a) Fiber displacements (node at fiber center) calculated with respect to temperature for different adhesive thickness. **(b)** At temperature 125 $^{\circ}\text{C}$, fiber shift with respect to the adhesive thickness.

the X- and Y- displacements of the fiber center, when the fiber is not equi-distant from the inclined V-groove walls. In this case, the X-displacement of the fiber is non-zero due to the unsymmetrical position of the fiber in the groove. The X-displacement of the fiber

Figure 5.6 Calculated fiber displacement shifts as a function of adhesive thickness between the fiber and the left wall of V-groove. Fiber is assumed to be in unsymmetrical position in the V-groove. Fiber distance from both the walls is considered same for the gap of 10 micrometer.

is found to be less than 0.2 μm and the slope of the variation is also small (Figure 5.6). Thus, the main reason for the optical loss in V-groove type optical module is the fiber shift in the Y-direction while the silicon V-groove helps in constraining the displacement in the X-direction. The displacement of the fiber in the asymmetric condition is more than that in the symmetric case for the same increase in temperature, as shown in Figure 5.7. Thus it is better to place the fiber symmetrically with respect to the inclined walls to avoid optical coupling loss due to the misalignment.

Next, the effect of bulk adhesive on the fiber displacement is studied. Figure 5.8 shows the displacement of the fiber center with respect to the adhesive area. A four-fold increase in adhesive area causes a shift of less than 0.1 μm in the fiber center. Thus, an increase in the amount of adhesive does not affect the displacement of fiber significantly.

Figure 5.7. Comparison of Y-displacement for asymmetric and symmetric position of the fiber in V-groove.

Figure 5.8 Displacement of fiber center with adhesive area. Fiber is placed at a distance of 10 micrometer from both inclined walls of V-groove.

5.4.2. Displacement measurement Results

Figure 5.9 shows the fringe patterns representing the displacement fields in the X and Y direction respectively for a fiber-adhesive bond at room temperature, 60°C, and 100°C respectively. From the fringe patterns it can be seen that the fringe density increases as the modules are subjected to higher temperatures. In the same figure, it can be seen that the number of fringes in the epoxy area exceeds the number of fringes in the silicon substrate because of the high CTE of the epoxy compared to the silicon substrate (Table

5.1). The recorded fringe patterns obtained by MMI were used to find the displacements U and V in the X and Y directions respectively of the center of single mode fiber with respect to the silicon substrate via equation 2.

$$U = \frac{\Delta N_x}{f} \qquad V = \frac{\Delta N_y}{f} \qquad (12)$$

where ΔN_x and ΔN_y are changes in the fringe orders in the X and Y directions respectively and f (2400 lines / mm) is the spatial frequency of the reference grating. From the X displacement field patterns, the number of fringes from one edge of the V-groove to the center of the fiber is calculated while from the Y -displacement field pattern, the number of fringes from the lower vertex of the V-groove to the center of the fiber is calculated.

Figure 5.9 Displacement Field a) X -direction and b) Y -direction for the fiber-adhesive joint sample 1 (Figure 2a)

Figure 5.10 Measured and calculated displacement of Fiber center of sample 1 (Figure 5.2a).

Figure 5.11 Measured and calculated displacement of Fiber center of sample 2 (Figure 2b).

5.4.3. Comparison and Discussion between FEA, and Experimental Results

Figures 5.10 and 5.11 compare the displacement components of the fiber center for the two modules determined by MMI and FEA. The FEA simulation and the MMI experimental results for the fiber shift of the two modules at different temperatures agree well with each other. This displacement was induced by the interaction of expansions in

fiber, epoxy and silicon substrate, with the contribution from the epoxy being the largest due to its high CTE value (Table 5.1). From the graphs it can be seen that the magnitude of the vertical displacement for the fibers is larger than that of the horizontal displacement. This is due to the confinement of the optical fiber and the epoxy within the V-groove in the horizontal direction (Figure 5.4). On the other hand, the vertical expansion of epoxy, being unrestricted, allows the optical fiber to move in the vertical direction (Figure 5.4). Similar results for X- and Y- displacements were found in the FEA simulation as well. Although the modules showed similar trend in the displacements, the amount of vertical displacements were different. At 100°C, the maximum vertical displacement in module 1 is about 0.7μm while for the module 2 it is 1.2μm. The difference is caused by the difference in initial positions of the fibers with respect to V-groove walls (Figure 5.4). In other words, the amount of adhesive between outer surface of the fiber and the wall affects the vertical displacement. A small horizontal displacement was also observed in the module, which was due to the off-center placement of the fiber in the V-groove.

5.4.4 Fiber Misalignment due to Thermal cycle (Viscoelastic model)

Figure 5.12 illustrates the displacement of the center node of the optical fiber for the thermal cycle. The maximum temperature is 85°C, which is slightly greater than the glass transition temperature (70°C) of the adhesive. One of the critical tasks on computing the stress/strain in the adhesive was to determine the reference state. In other words, at what temperature and what time, can the adhesive joint be treated as a stress/strain free state? One obvious choice is the beginning of the thermal cycle at room temperature (25°C). The main aim of this simulation is to determine the shift of fiber with changes in temperature. Thus room temperature was chosen as reference and stress free temperature. Since the UV-curing is a room temperature process and no external heat is supplied, thermal stress developed during the UV-curing process can be assumed to be minimal in the adhesive joint at room temperature. Maximum displacement of fiber center in X- and Y-direction occurred at -40°C, which is during the shrinkage of the adhesive. Maximum displacement during the first thermal cycle in X-direction is 0.23μm and in Y-direction is

0.62 μm . It is expected because of the constraints created by V-groove for the fiber displacement in the X-direction (discussed in detail in the case of elastic modeling).

(a)

(b)

(c)

Figure 5.12. Displacement of optical fiber center in X- and Y- direction over (a) 100 cycles (b) 12 cycles and (c) first cycle

Increasing the temperature induces a compressive stress in the adhesive between the optical fiber and SiOB walls because expansion of the adhesive is constrained at V-groove walls. These compressive stresses relax at an accelerated rate due to the increased temperature, which makes the optical fiber move towards the V-groove walls. When the material is cooled, stress relaxation at the hot temperature is reflected in increased compressive stress in the optical adhesive at the cold temperature (Figure 5.14 and 5.15). These stresses cannot be fully relieved before the next cycle begins because of the slow rate of relaxation at colder temperatures. Different rates of relaxation for hot temperature and cold temperature is reflected by the fiber displacement rate during the period of constant temperature (Figure 12 b). Each full temperature cycle therefore results in an increased displacement of the fiber at the low temperature. The fiber displacement begins to plateau with increasing cycles because of the thermal cycle profile and constraint created by the V-groove walls for the expansion of adhesive (Figure 12 a).

Figure 5.13. Different FEA model elements selected to scrutinize stress around the optical fiber due to thermal cycle.

Figure 5.14. Stress developed at various elements (defined in Figure 5.13) in X-direction.

Figure 5.15 Stress developed at various elements (defined in Figure 5.13) in Y-direction.

Displacement of the optical fiber takes place according to the expansion and shrinkage in the optical adhesive. Expansion and shrinkage in adhesive at a constant temperature depends on the relaxation in adhesive with time at that temperature. A mechanism that involves changes in the frictional forces as a function of time within the temperature cycle can explain the relaxation in the adhesive at hot and cold temperature. As the optical module is heated, the adhesive expands exerting larger pressures on the interface with the SiOB. This large pressure results in high frictional forces, which tend to prevent sliding of the adhesive along the V-groove walls. At these elevated temperatures, viscoelastic flow within the adhesive is accelerated because of the increased molecular mobility. Because the adhesive is partially confined within the V-groove, adhesive tends to flow along the Y-direction with increase in temperature. The pressures at the interfaces are reduced during the dwell time at high temperature, as this flow takes place. Due to

reduction in pressure the frictional force also reduces at the interface. Adhesive starts moving along the silicon walls of V-groove and stress relaxation is expected. Relaxation at high temperature in the optical adhesive reduces the displacement of optical fiber with time (in both X- and Y- direction, Figure 5.12b). When the material is cooled, stress relaxation at the hot temperature is reflected in increased residual tensile stresses at the cold temperature. These stresses cannot be fully relieved before the next cycle begins because of the slow rate of relaxation at colder temperatures. No significant change in fiber displacement at cold temperature is observed during the dwell time (Figure 5.12b). Each full temperature cycle therefore results in an increased displacement value at the low temperature. As a result, over a definite number of cycles, this flow results in a significant amount of displacement of the optical fiber which is embedded in the adhesive (Figure 5.12a). As the temperature is lowered, the adhesive exerts less pressure on the silicon walls because it tends to shrink towards the fiber surface from all directions. If the temperature range is sufficient, the adhesive may actually get separated from the walls.

Frictional force induced between silicon wall and adhesive materials depends on the pressure or bearing stress, which is time dependent. At high temperature the friction force is decreased with time which brings the relaxation in adhesive materials, and this change is reflected at low temperature also. At low temperature, frictional force is not able to attain its original state because of slow rate of relaxation. Thus, this mechanism rests on the premise that a hysteresis loop is present for the frictional forces for viscoelastic materials present in partially confined configurations.

5.4.5 Parameter sensitivity on the optical fiber displacement

Displacement summary of optical fiber in a given thermal cycle depends on the residual stress magnitudes or the rate of viscoelastic relaxation of the adhesive. These properties of the adhesive depend on the materials properties such as stiffness, CTE, and T_g as well on the range (high and low temperature) and dwell time of the temperature cycle. Increasing the CTE results in increased strain and therefore increased stress while decreasing CTE has the opposite effect. When the material is glassy for the entire

thermal cycle (maximum cycle temperature is less than or equal to T_g), the maximum stress possibly built into the system can be a product of glassy stiffness, CTE, and temperature difference. In Figure 5.16, displacement of optical fiber center is simulated for the temperature cycle of 25°C to 70°C (T_g of adhesive is 75°C) and dwell time is 15 mins. Stress is not able to recover in this case, which is reflected by displacement curve (Figure 5.16). When the hot temperature for cycling falls below the glass transition region then only an insignificant amount of stress relaxation has taken place during the entire thermal cycle. Stress developed or relaxed in the adhesive joint also depends on the thermal cycle profile. As shown in figure 5.17, when the dwell time is increased to 2hr (temperature cycle of -40°C to 85°C) the displacement curve reaches a plateau within a few cycles. Increase in the dwell time of thermal cycle results in reduced residual stress level in the adhesive. As the temperature is constant for a longer time, there is more time for adhesive to undergo stress relaxation at the high temperature dwell. As explained in previous section, stress relaxation during the low temperature dwell time is insignificant. Thus, no change in the displacement profile of the fiber center is observed (Figure 5.17). The viscoelastic effect can be minimized if adhesive of low CTE and high T_g is selected for the optical modules. This parametric study can play significant role in deciding the adhesive materials properties required for the joint.

Figure 5.16. Displacement of optical fiber center in X- and Y- direction over 100 cycles for temperature cycle from 25°C to 70°C.

Figure 5.17. Displacement of optical fiber center in X- and Y- direction over 100 cycles for dwell time of 2hrs.

6. Optical Coupling Efficiency Studies of Optical Module

Under ideal alignment conditions in butt coupling, an optical coupling efficiency of less than 30% can be achieved for laser diode and single mode fiber (wavelength 1550nm). Some references have reported practical butt-coupling efficiencies as low as 10% [131]. Optical losses for ideal alignment are mainly due to the mode mismatch between SMF and LD. Loss can also be attributed to: a) dimensional uncertainty of optical elements (laser diode, fiber and lens) and SiOB, and b) device shift during attachment process. Analysis of coupling efficiency and possible transverse and angular misalignment losses of a laser diode to single-mode, step-index fiber is presented in detail here. Optical analysis used here employs ABCD matrix for change in Gaussian beam while traveling through vacuum or any medium, which makes the analysis simpler compared to other complicated methods. The coupling efficiency was calculated using the overlap integral method [3-5, 39].

A brief discussion of ABCD matrix theory is presented in section 6.1. ABCD matrix details can be found in reference [39]. A general description of Optical coupling efficiency calculation theory has been given in section 6.2. Coupling of laser diode to single mode fiber alignment is analytically studied in section 6.3. Effects of above mentioned parameters on the coupling loss of laser diode to SMF on SiOB are analyzed. In section 6.4, optical coupling loss due to the misalignment (determined by FEA viscoelastic analysis) of optical fiber produced by thermal cycle is calculated and compared with experimental results.

6.1 Ray / ABCD Matrix

Ray matrices or “ABCD matrices” are widely used to describe the propagation of geometrical optical ray through paraxial optical elements, such as lenses, curved mirror or an optical medium. Translation, reflection and refraction are the basic operations for a ray traveling through optical medium. Consider a ray of light traveling approximately in the z-direction, but with a transverse displacement $r(z)$ from the axis and a small slope of

dr/dz . If such a ray travels in free space from a point z_1 to another plane at $z_2 = z_1 + L$, its input and output ray coordinates will be related by the transformation

$$r_2 = r_1 + L \, dr_1/dz \quad (1)$$

$$dr_2/dz = dr_1/dz \quad (2)$$

These equations are of form as described below:

$$r_2 = A \, r_1 + B \, r'_1 \quad (3)$$

$$r'_2 = C \, r_1 + D \, r'_1 \quad (4)$$

It is then natural to write equation (3) and (4) in matrix form as

$$\begin{bmatrix} r_2 \\ r'_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} r_1 \\ r'_1 \end{bmatrix} \quad (5)$$

where ABCD matrix is the ray matrix for an optical element. From equation (1) and (2)

ABCD matrix for translation case can be written as

$$\begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \quad (6)$$

Similarly, for other operations i.e, reflection and refraction, 2×2 matrices (ABCD matrix) can be formulated as given below:

$$\begin{bmatrix} 1 & 0 \\ \frac{2n}{R} & 1 \end{bmatrix} \quad (7) \quad \begin{bmatrix} 1 & 0 \\ \frac{n-n'}{n'R} & \frac{n}{n'} \end{bmatrix} \quad (8)$$

Reflection

Refraction

where R is the radius of curvature of surface, n and n' are refractive indices of the mediums in which light was traveling initially and finally respectively. A ray can be traced through an optical system by repeatedly applying translation, reflection and refraction matrices to the original ray vector. The system matrix (A) is the product of all the three matrices for an optical system (from the first vertex to the last vertex). One of the most important uses of this form of matrix optics is the ABCD law. This law is used to calculate beam waists and radii of curvature for Gaussian laser beams. A complex characteristic function (q) of the Gaussian beam is defined through the following relation:

$$\frac{1}{q(z)} = \frac{1}{R(z)} - i \frac{\lambda}{\pi \omega^2(z)} \quad (9)$$

where R and ω are the radius of curvature and beam waist for the Gaussian beam at distance z and λ is wavelength of the beam. The new characteristic function after passing through an optical system is given by the relation:

Figure 6.1. Schematic of optical coupling with a lens

$$\bar{q}_2 = \frac{A \bar{q}_1 + B}{C \bar{q}_1 + D} \quad (10)$$

where A , B , C and D are the elements of the system matrix and characterize the paraxial focusing properties of the optical system. This law is extremely useful in calculating the diffraction limited beam waist and location of a laser beam passing through any optical system provided its system matrix is known [39].

The change in Gaussian beam field emitted by single mode laser diode and passing through the lens (as shown in Figure 6.1) was analyzed with the help of ABCD law. ABCD matrix for this system can be written as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & z_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & z_2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 - \frac{z_2}{f} & z_1 + z_2 - \frac{z_1 z_2}{f} \\ -\frac{1}{f} & 1 - \frac{z_1}{f} \end{bmatrix} \quad (11)$$

Laser beam, emitting light of 1310 nm-wavelength and initial beam waist size $3 \mu\text{m}$, was considered to study the variation of waist size with different parameters like focal length, LD-lens distance and lens-fiber distance. The beam waist size plays an important role in

coupling efficiency. The beam waist size should match with waveguide spot size to achieve minimal coupling loss. The effect of variation in laser diode-lens distance, lens focal length and lens-optical fiber distance on the laser beam waist is shown in Figure 6.2. The beam waist decreases with increase in the LD-lens or lens-fiber distance. Beam waist increases with increase in the focal length of lens. Varying the laser diode lens distance has very little effect on the final beam waist of the laser diode.

Figure 6.2. Beam waist variation for LD-Lens-Fiber system with different parameters (a) Fiber Lens Distance (b)Focal Length of Lens and (c) LD Lens. All dimensions are in μm .

6.2 Coupling Efficiency Calculation

A general laser-to-fiber coupling system is shown in Figure 5.6 where the field of an SMF is assumed to be symmetric. Single mode fiber can be described by a Gaussian beam with a beam waist radius of ω_{0f} . The field of a laser diode is elliptical, and has Gaussian distributions in both vertical and horizontal directions with unequal beam waist radii of ω_{0x} and ω_{0y} respectively. The coupling efficiency of such a system was calculated by the overlapping integral of these two fields in any plane between the end-faces of the fiber and the laser [61].

$$\eta = \frac{\left| \iint \psi_v^* \psi_f dXdY \right|^2}{\iint |\psi_v|^2 dXdY \iint |\psi_f|^2 dXdY} \quad (12)$$

where ψ_f and ψ_v are Gaussian fields of fiber and LD in the plane of integration. The coupling efficiency was calculated in the plane 1 as depicted in Figure 6.3. The more general coupling efficiency can be expressed as

$$\eta = \eta_x \eta_y \quad (13)$$

Where $\eta_x = \eta_z^{(x)} \eta_d^{(x)} \eta_\theta^{(x)} \eta_{d,\theta}^{(x)}$, $\eta_y = \eta_z^{(y)} \eta_d^{(y)} \eta_\theta^{(y)} \eta_{d,\theta}^{(y)}$

Figure 6.3. Optical Coupling between Astigmatic LD and Single Mode Fiber

$$\eta_z^{(x)} = \frac{2\omega_{2x}\omega_f}{\left[(\omega_f^2 + \omega_{2x}^2)^2 + \frac{k^2\omega_f^4\omega_{2x}^4}{4R_{2x}^2} \right]^{1/2}} \quad (14)$$

$$\eta_d^{(x)} = \eta_z^{(x)} \exp \left\{ \frac{2d^2}{\omega_f^2} * \left[\frac{\omega_{2x}^2(\omega_{2x}^2 + \omega_f^2)}{(\omega_f^2 + \omega_{2x}^2)^2 + \frac{k^2\omega_f^4\omega_{2x}^4}{4R_{2x}^2}} - 1 \right] \right\} \quad (15)$$

$$\eta_\theta^{(x)} = \eta_z^{(x)} \exp \left\{ -\frac{2k^2\theta^2}{2} \times \left[\frac{\omega_f^2\omega_{2x}^2(\omega_{2x}^2 + \omega_f^2)}{(\omega_f^2 + \omega_{2x}^2)^2 + \frac{k^2\omega_f^4\omega_{2x}^4}{4R_{2x}^2}} \right] \right\} \quad (16)$$

$$\eta_{d,\theta}^{(x)} = \eta_z^{(x)} \exp \left\{ \frac{2k^2\theta d}{R_f R_x} \times \left[\frac{\omega_f^2 \omega_{2x}^2 (R_x \omega_{2x}^2 + R_f \omega_f^2)}{(\omega_f^2 + \omega_{2x}^2)^2 + \frac{k^2 \omega_f^4 \omega_{2x}^4}{4R_{2x}^2}} \right] \right\} \quad (17)$$

Similarly, the expression of η_y is obtained by replacing x in (12)-(15) with y . To obtain the coupling efficiency of laser diode–SMF system with lens or other optical components in between, the overlapping integral (equation (11)) of the laser and the fiber fields has to be calculated in the end-face plane of the fiber. First, the beam radii and radii of curvature of the laser field in both horizontal and vertical directions are obtained from the ABCD law and these parameters were put in equation (11) to find the coupling efficiency of the system.

Figure 6.4. Coupling efficiency with misalignment for LD to Fiber butt coupling (a) x-shift, y-shift and angular misalignment (b) z-shift (distance is measured in μm)

6.3 Analytical study of laser diode to single mode fiber butt coupling on SiOB

Direct coupling efficiency of LD to single mode fiber on SiOB was calculated using the above equation. Laser diode emits radiation of wavelength 1310 nm with spot sizes of 7

μm and $3\ \mu\text{m}$ in x and y directions respectively. Mode mismatch between the Gaussian beam and the optical fiber plane is not included; only the ellipticity of the Gaussian beam is considered. The aim of this calculation is to observe the effect of misalignments in different directions on the coupling efficiency. The step-index fiber core diameter was measured to be $8.5\ \mu\text{m}$ using a high resolution optical microscope. The spot size of the optical fiber was calculated to be $9\ \mu\text{m}$, based on the measured core diameter. Here, coupling loss due to misalignment in transverse and angular direction has been considered. Coupling loss due to misalignment in x, y, z and θ was calculated with matlab simulation for LD-fiber alignment. The effect of z-direction misalignment was found to be negligible compared to x, y and θ direction (Figure 6.4). In z-direction, coupling efficiency shows a maximum value (Figure 6.4(b)). Maximum coupling efficiency is observed at the point where waist sizes in both x- and y-direction match with the spot size of fiber. Angular misalignment has greater effect on coupling loss compared to transverse misalignment. In Figure 6.4(a), coupling efficiency loss due to x-direction transverse misalignment is less than x-direction angular misalignment. Coupling loss is directly proportional to divergence angle. Laser diode has greater divergence angle in y-direction (less initial waist size) than the divergence angle in x-direction. Coupling loss in y-direction due to transverse misalignment is higher compared with the transverse misalignment in x-direction (Figure 6.4(a)). This effect is due to the elliptical shape of Gaussian beam emitted by laser diode.

Theoretically, optical coupling efficiency of 55% (-2.6dB) can be achieved in SMF and LD (wavelength 1310nm) if the two are perfectly aligned on the silicon optical bench. Optical losses for ideal alignment are mainly due to the mode mismatch between SMF and LD. Additional sources of loss include: a) dimensional uncertainty of optical elements (laser diode and fiber) and SiOB, and b) device shift during attachment process. The effect of these parameters on coupling loss has been analytically analyzed and is discussed in greater detail in the following sub sections.

6.3.1 Effect of Mode Mismatch

To study the effect of mode mismatch between LD and SMF, coupling efficiency is calculated by solving the equation (11) for elliptical LD beam.

$$\eta_0 = \frac{2\omega_x\omega_f}{\left[(\omega_f^2 + \omega_x^2)^2 + \frac{k^2\omega_f^4\omega_x^4}{4R_x^2}\right]^{1/2}} \times \frac{2\omega_y\omega_f}{\left[(\omega_f^2 + \omega_y^2)^2 + \frac{k^2\omega_f^4\omega_y^4}{4R_y^2}\right]^{1/2}} \quad (18)$$

where ω_x and ω_y , and R_y and R_x are beam waist and radii of curvature of the laser diode in x- and y-direction, respectively, in the coupling plane. ω_f is the spot size of single mode fiber (approximately 9.0 μm for the single mode fiber), and k is wave number. Initial laser diode beam waist in x-direction is 1 μm and varies in y-direction from 1 to 3.5 μm . Initial beam curvatures of LD are taken as infinite. Final beam waist and coupling efficiency were calculated for an elliptical LD and a circular SMF with a separation of 20 μm and are shown in Table 1. Final beam waist size of LD is inversely related to the initial beam diameter, the divergence angle, and the distance traveled by the beam. An optical loss of 15% was calculated for a 40% change in the ellipticity of initial beam. Ellipticity and eccentricity are the two factors of single mode fiber (SMF) that contribute to mode mismatch. The ellipticity and eccentricity of a commercially available single mode fiber were measured experimentally to be 0.212% and 0.2 μm , respectively. These values are significantly less than laser diode ellipticity and were ignored in the calculation.

6.3.2 Effect of uncertainty of SiOB dimensions

The misalignment due to structural fabrication from the designed value also causes additional loss. The variation in V-groove width causes transverse misalignment, whereas the variation in U-groove dimensions causes transverse as well as lateral misalignments of the SMF. Analytical equations were determined to calculate the effect of the variation of V-groove width on coupling efficiency (η_d) for the LD-to-SMF

coupling using equation 11 and 18. The coupling efficiency was determined to be an exponential function of width deviation as shown in equation 19.

$$\eta_d = \eta_0 \exp \left\{ \frac{2d^2}{\omega_f^2} * \left[\frac{\omega_y^2 (\omega_y^2 + \omega_f^2)}{(\omega_f^2 + \omega_y^2)^2 + \frac{k^2 \omega_f^4 \omega_y^4}{4R_y^2}} - 1 \right] \right\} \quad (19)$$

where d is the misalignment in the Y-direction and is equal to

$$d = \Delta w * \tan(54.7^\circ) \quad (20)$$

where Δw is deviation in SiOB upper width from design value, and 54.7° is due to KOH etching process of silicon (100) planes. Optical losses of more than 15% were observed with a 3 μm deviation of the V-groove width (Figure 6.5). It is thus critical to control the dimensions of the SiOB during fabrication to within $\pm 1\mu\text{m}$ accuracy to achieve passive alignment. Control of SiOB dimensions is one of the biggest challenges faced in passive alignment technology for achieving high coupling efficiency. The reasons for deviation in SiOB dimensions from the designed value were presented in chapter 3, where the fabrication of SiOB with sub micron accuracy has also been discussed.

Figure. 6.5. Optical coupling loss due to the relative misalignment of laser diode and single mode fiber in silicon optical bench.

Figure 6.6. (a) Schematic of Fiber attached with adhesive in V-groove. (b) Vertical misalignment corresponding to adhesive thickness (μm) as shown in picture a. (c) Optical losses caused by the separation of fiber from the V-groove sidewalls due to varying adhesive thicknesses.

6.3.3 Effect of Attachment Process

In a properly made SiOB, attachment of different components itself can cause misalignments in the module. The design of SiOB pre-supposes a direct contact between the optical fibers and the V-groove wall. UV-curable adhesives that facilitate very short cure times are used to attach the SMF to SiOB to minimize the fiber movement during the attachment process. Adhesives may become entrapped between the SiOB wall and

fiber due to (i) lack of appropriate pressure during placement, (ii) spring back effect, (iii) excessive adhesive volume, and (iv) material shrinkage during the attachment process (Figure 6.6a). Analytical analysis was carried out to quantify the fiber misalignment due to adhesives and the coupling losses were estimated (Figure 6.6b and 6.6c). It is assumed in this analysis that the adhesive thickness is uniform on both sides of fiber. Due to the symmetric position of fiber in V-groove, misalignment in the assembly occurs only in the y - direction. In reality, thickness is not uniform on both sides of fiber, due to which misalignment take place takes place in both Y- and X- directions (discussed in previous section). Optical coupling loss for uniform adhesive distribution around the fiber is calculated by equation 19, where d is the misalignment in Y-direction due to adhesive layer (Δr) between Si wall and fiber and is given by following equation

$$d = \Delta r / \cos (54.7^\circ) \quad (21)$$

Optical Coupling efficiency reduces by as much as 15% even for a thin 1- μm layer of adhesive (equivalent to 1.73 μm of y-direction misalignment Figure 6.6b) between the SMF and the V-groove wall, and by 50% for a 2 μm layer (3.46 μm y-direction misalignment). The problem is thus more severe than the problems caused by dimensional deviations in SiOB and LD. Therefore, to avoid this major source of coupling loss, it is necessary to keep the fiber in contact with silicon groove wall during assembly. Details of the fiber attachment process to achieve this condition were discussed in the experiment chapter.

In summary, the important parameters that determine the acceptance of passive alignment methods are

- 1) misalignment of optical elements due to dimensional uncertainty of SiOB
- 2) The attachment process parameters.

The dimensional inaccuracy of the laser diode is another significant factor for coupling loss and should be considered during SiOB design, which was described in chapter 3. It is found that the coupling efficiency does not degrade with the fiber eccentricity and ellipticity and hence is not considered hereafter.

6.4 Measured Optical Coupling Efficiency

SiOB groove width and depth were measured using an optical microscope and a scanning electron microscope. A V-groove SiOB of upper width 169 μ m and depth 118 $\pm$ 1 μ m, and a U-groove of width 320 $\pm$ 2 μ m and depth 75 $\pm$ 0.5 μ m were achieved. The dimensions were found consistent with a $\pm$ 1 μ m precision across different wafers as well as within the same wafer. Figure 6.7 show optical microscope and SME image of the fabricated SiOB.

Figure 6.7 Cross section SEM picture of U- and V-groove of fabricated SiOB

The apex of the U- and V-grooves has a convex curvature, caused by undercutting. Compensation structures have been suggested to counter undercutting in actual mask designs so as to alleviate this issue. These convex shapes are not expected to affect the quality of optical interconnects.

The cross sections of the assembled module of fiber-attached V-groove are shown in Figure 8. It is worth noting that the adhesive did not allow contact between the V-groove and optical fiber. It is performing only the desired function of keeping the components intact. Furthermore, the gap is not the same on both walls of the V-groove and was found to vary between 1 and 3 μ m. As discussed previously, this phenomenon is a critical source of misalignment in optical modules. Corresponding losses of 20-60% can be estimated from the graphs of Figure 6.6. Thus, control of this gap was an essential challenge that was addressed for successful deployment of passive alignment techniques in the packaging of transceiver modules.

Figure 6.8.Cross section of fiber in V-groove highlighting the gap between the fiber and Si wall.

6.4.1 Fiber to fiber coupling on Silicon Optical Bench

The effect of fiber displacement due to the curing on coupling efficiency was experimentally examined. The result of coupling loss for fiber-to-fiber alignment on SiOB (twelve samples were tested) is shown in histogram of Figure 6.9. Power loss due to connector was found to be less than 15%, and power loss due to reflection was only 6-7 %. The optical coupling loss after adhesive attachment process varies between 20% and 35% (Figure 6.9). This loss is attributed to the varying gap between the SMF and V-groove walls, and the gap between two fiber tips along the fiber axis. In the experiment, both the fibers are attached with adhesive in SiOB. It is crucial to find out the accurate shift of one fiber with respect to the other in order to determine the misalignment using analytical analysis. The exact optical loss is calculated from the misalignment value determined using coupling equations. The SEM picture (Figure 6.8) shows varying adhesive thickness of 1-3 μ m between the fiber and inclined wall for different samples. Similar loss was found in optical modeling for adhesive thickness less than 2 μ m between fiber and V-groove wall (Figure 6.6). From both modeling and experimental results, it is clear that the movement of fiber during attachment process plays a critical role in determining the coupling efficiency of the module.

Figure 6.9 Histogram of optical coupling loss measurement for fiber-to-fiber alignment on SiOB for 12 samples.

6.4.2 Laser diode to the fiber coupling on the optical bench

Coupling efficiency of laser diode to single mode fiber aligned on the silicon optical bench was determined by measuring the external differential efficiency of the fiber output against that of the laser output. For the butt joint, the spacing between laser diode and single-mode fiber must be reduced to as small a value as possible. In this experiment, the spacing is approximately 10 μm . Optical coupling efficiency for 30 modules assembled on the SiOB (assembly process is detailed in chapter 3) was measured and is shown in Figure 6.10. Optical coupling results are quite scattered from one module to another because of the passive alignment process of optical fiber with respect to laser diode. Maximum optical coupling of 27% was achieved on the fabricated SiOB using the butt coupling. Major contributor to the optical coupling loss of the module is the mode mismatch between laser beam and optical fiber (as discussed in the analytical section), and misalignment introduced between the laser diode and fiber during the assembly process. The adhesive curing process was adding an approximately 25-35% of optical coupling loss to the total coupling because of fiber displacement on the V-groove (discussed in last section). Laser diode was fixed with the help of the Au-Sn solder preform, and shrinkage in the solder is negligible compare to the polymer adhesive. Thus, it can be assumed that the misalignment effect which is coming in the optical module is mainly due to fiber attachment process and SiOB dimension uncertainty. Further degradation of optical alignment takes place due to temperature conditioning as discussed in the chapter 4.

Figure 6.10. Histogram of optical coupling loss measurement for 30 optical module samples.

Medium refractive index	Coupling efficiency (%)
1.0	25
1.4	26.23
1.43	26.7
1.46	27
1.5	26.6

Table 6.1 Calculated Coupling Efficiency for different mediums

6.4.3 Effect of index matching material on the coupling efficiency

Optical coupling efficiency was calculated for index matching gel with different refractive index (as shown in Table 6.1). It is assumed that initial (when there is no index materials) coupling efficiency of the system is 25%. Index matching gel is used to avoid the reflection loss due to sudden change in refractive index of medium. Index matching materials also affected the Gaussian beam shape depending on the material refractive index value, which is clear from the beam waist calculation formulas. If the affect of index materials on Gaussian shape was negligible then an increase of ~3% (-14.7dBm) in optical coupling would take place for the refractive index of 1.46. Due to the change in beam waist and radius of curvature of the laser beam by the index matching material the calculated coupling efficiency is less than 27%.

The coupling efficiency of 10 assembled samples were measured after and before introducing the optical adhesive. A large variation in coupling efficiency change due to bring in of the adhesive was observed for the samples. In only 2 samples, increase of the coupling efficiency by less than 2% was observed. In rest of the samples coupling efficiency was decreasing. Decrease in coupling efficiency took place due to not uniform curing of the adhesive between the laser diode and the optical fiber. Curing stress was developed in the optical adhesive, which obstacle the path of the laser diode beam. It is very important to cure the optical adhesive perfectly, when it is used as index matching material, to enhance coupling efficiency by avoiding the reflection losses.

Finally the effect of refractive index change of the optical adhesive by environmental conditions (temperature and humidity) on the module optical coupling was studied analytically. Refractive index of optical adhesive changed from 1.46 to 1.433 by increasing the temperature from room temperature to 120°C (Figure 4.1). Corresponding decrease in the coupling efficiency is 26.21% from 27%. Refractive index change of the optical adhesive by humidity was found comparatively lower (Figure 4.2) thus effect on the optical coupling is not much. But, it was observed a permanent change in the refractive index of the optical adhesive, which can bring permanent change in optical coupling also for the devices operated in high humid environment.

6.5. Effect of Temperature Conditioning on Optical Coupling Efficiency

The ruggedness of the assembled optical modules was tested for the thermal cycle conditions according to the Telcordia-GR-1221-CORE standards. Finite element analysis data for the optical fiber shift was introduced in the optical coupling analytical equation as X- and Y-misalignment of the optical fiber in the V-groove. Degradation of the laser diode output and at the solder joint due to thermal cycle is neglected in this study. Figure 6.11 shows the calculated optical coupling for the laser diode to optical fiber alignment on SiOB for 100 thermal cycles. It is assumed that maximum coupling efficiency (without any thermal treatment) for this calculation is assumed to be 25% in Figure 6.11a and 94% in Figure 6.11b. Important point to be noted here is the increase in the fluctuation width of the optical coupling efficiency increases with the number of thermal

cycle. This trend can be explained with the help of FEA result for the fiber displacement (Figure 5.12). At the end of each thermal cycle, fiber displacement was tending towards zero displacement at high temperature but at the same time the displacement was increasing (in negative side) at low temperature. This change was steeper for the Y-displacement compared to the X-displacement. Rise in the coupling efficiency can be seen at high temperature because of the Y-displacement of the fiber is going towards zero. At low temperatures, the displacement for both directions is becoming more and more negative, which makes the optical coupling worse for the module.

Second important point to notice in Figure 6.11 is the fluctuation width depends on the initial coupling efficiency. In Figure 6.11a coupling efficiency variation at the end of 100th cycle is of less than 2% (23% to 24.94%), but in Figure 6.11b it is more than 7% (86.5% to 93.74%). If the variation in coupling efficiency is normalized with respect to the initial coupling value, it is same for both cases. This effect seems to be inversely related to the initial coupling efficiency. If the coupling efficiency is high then variation in coupling efficiency is also high and vice versa. As discussed in the preceding sections, the main factors which add to the initial coupling loss are mode mismatch and misalignment between optical elements. Thus mode mismatches and / or initial alignment of the optical fiber also contribute to determination of the reliability of the optical module for long time.

Optical coupling efficiency of the assembled module was measured after 100 cycles. It is compared with the maximum and minimum of analytical determined value in table 6.2. Analytical values were calculated on the base of initial coupling efficiency of the respective optical modules. It is observed that in most of the cases optical coupling has degraded for the optical module and the final coupling efficiency lies between the maxima and minima of the calculated efficiency. The degradation in final optical coupling is not significant (<3%), but more important is fluctuation of the optical output value during a given cycle.

Figure 6.11. Calculated coupling efficiency of the optical module is plotted against time for the 100 cycles. Initial coupling efficiency is considered to be (a) 25% and (b) 94%. Misalignment in X- and Y-direction was incorporated from the FEA data.

Initial optical coupling efficiency (%)	Analytically calculated		Experimentally determined (%)
	Minimum	Maximum	
12	11.09	12.02	10.5
16	14.66	15.9	15.2
19	17.47	18.95	18.5
20	18.4	19.96	17.2
21	19.31	20.94	21.2
22	20.21	21.91	22
25	23	24.94	23.7
26	23.96	25.98	25.01
27	24.85	26.95	25.72

Table 6.2. Comparison of optical coupling efficiency analytically calculated and experimentally measured for the module after 100 cycles.

7. Conclusions and Future Works

7.1 Conclusions

- a) Optical adhesive was used for dual purpose in this research work: 1) For the attaching the optical components and 2) fill the gap between optical components. Thus, Optical adhesive affects the optical coupling of the optical module also in two ways 1) Misalignment in the optical fiber depends on the adhesive thermo-mechanical properties and 2) change in the optical properties of the adhesive affects the light transmission in the gap.
 - 1. The Optical adhesive thermo-mechanical properties characterization was done to analyze the optical fiber shift by the Finite element analysis. Optical adhesive shows two CTE values, CTE 1 ($151.2 \times 10^{-6} / ^\circ\text{C}$) and CTE 2 ($217.5 \times 10^{-6} / ^\circ\text{C}$) for temperatures below and above T_g respectively. Temperature dependent storage modulus was determined using the DMA and maximum value of 1.26GPa was observed.
 - 2. Viscoelastic property of the optical adhesive was determined using the time-temperature superposition (TTS) method. Modulus of the adhesive was determined for the multifrequency by DMA for a temperature range from 25°C to 200°C . Master curves was obtained by shifting the initial multifrequency curves to a reference temperature of 343 K (70°C) using the WLF model. Adhesive viscoelastic property was used in the FEA to determine the optical fiber shift for the thermal cycles.
- b) The impact of temperature, moisture and annealing, on the refractive index of the optical adhesive was studied. These optical properties characterization of the adhesive provides useful insights into the reliability of optoelectronic devices and components assembled with the optical adhesive.
 - 1. Refractive index of optical adhesive was measured by OTDR and prism coupling methods. Refractive indices decreased with increasing temperature because of the decline in the density of the adhesive material. At glass transition temperature an abrupt change in the Thermo-optic coefficient takes place.

2. Refractive index of the adhesive was studied during the moisture desorption and found to be increasing with decrease in moisture content. The rate of change in refractive index also depends on the temperature of desorption.
 3. A permanent change in refractive index was also observed due to moisture absorption in the optical adhesive.
 3. The rate of refractive indices changes with annealing temperature has positive values, but the slope of the increment for T_E mode refractive index is less than T_M mode. Increase in the refractive index due to annealing is suggested to result from volume relaxation. Birefringence of the optical adhesive decreased with annealing temperature which may happen because of the adhesive is becoming more isotropic.
- c) Fiber center shift is examined numerically and experimentally in the fiber-adhesive joint on SiOB subjected to the thermal loads. The following conclusion can be drawn from this study.
1. The effect of the adhesive layer thickness and the bulk adhesive amount on the fiber shift has been shown by numerical analysis. As a result, it is seen that the Y-shift increases with an increase in the adhesive thickness and X-shift decreases as the fiber is placed symmetrically in the V-groove. It was also found that the effect of bulk adhesive on the optical fiber shift was negligible for the fiber-adhesive joint in V-groove.
 2. For a given adhesive thickness between the fiber and the inclined walls, the fiber displacement was found to change linearly with the temperature. The major cause of fiber shift comes from the adhesive expansion because of its high CTE value compared to the silicon and the optical fiber. The fiber displacement according to FEA calculation is $\sim 1.0 \mu\text{m}$, for fiber-adhesive joints on SiOB, with an adhesive layer thickness of $10 \mu\text{m}$ at 125°C .
 3. Micro Moiré interferometry was used to understand the *in-situ* submicron level displacement of the single mode fiber center during a temperature cycle. Maximum displacement of the fiber center in the vertical and horizontal directions with respect to the SiOB was measured to be $0.69\text{--}1.21\mu\text{m}$ and $0.36\text{--}0.42\mu\text{m}$, respectively at 100°C .

4. Experimental results were compared with finite element analysis and were found to be in close agreement. Thus, it is shown that MMI is an effective tool to measure the misalignment of the optical components and its application can be further extended to study the fatigue failure of the optical modules.
- d) Investigation of the optical coupling efficiency of the optical module.
1. The coupling performance of the passively aligned optical module was studied with respect to dimensions of SiOB and attachment process. Assessment of coupling losses was done by analytical equations, and showed a significant loss of 15% for a $3\mu\text{m}$ deviation of SiOB dimensions and for a $1\mu\text{m}$ fiber/SiOB wall gap. Mode mismatch between laser diode beam and optical fiber add significantly to the optical coupling loss of the module.
 2. Silicon optical bench with V-groove, and U-groove was fabricated by the anisotropic etching process and dimension accuracy of $\pm 1\mu\text{m}$ was achieved. Assembly of test vehicle was carried out on SiOB by attaching the optical fiber with the adhesive and laser diode by solder. Optical modules were also assembled by introducing the optical adhesive in light passing section between the laser diode and optical fiber.
 3. In the fiber to fiber alignment on the SiOB, average optical coupling loss due fiber misalignment was found to range from 20% (best case) to 30%. Experimentally obtained value of optical coupling loss ($\approx 30\%$) due to the fiber misalignment was in good agreement with that of the mathematical simulation.
 4. Optical coupling results for the laser diode to the optical fiber were quite scattered from one module to another because of the manual alignment process of the optical fiber with respect to the laser diode. Maximum optical coupling of 27% was achieved on the fabricated SiOB using butt coupling.
 5. Optical adhesive as index matching material was used to avoid the reflection loss at the optical fiber surface. A gain of 2% in optical coupling was observed for the modules using the optical adhesive in between the LD and the fiber. Index

materials minimize the reflection loss and also affect the laser beam shape. Thus the effect in coupling efficiency is the net effect of these two factors.

6. A complete assessment of the tolerances involved in design and assembly, as well as diligent process optimization and control of SiOB dimensions will thus pave the way towards improved alignment and minimized optical losses in the passive alignment technology.
- e) Reliability study of the optical modules:
- Displacement profile of the optical fiber center was calculated for the thermal cycle by finite element method. The temperature was cycled between 85°C and -40°C with 5 minute ramp and 15 minutes holds.
 - Maximum displacement during the first thermal cycle in X-direction is 0.23μm and in Y-direction is 0.62μm. X-displacement for the optical fiber was constrained by the V-groove walls because the adhesive expansion was restricted by the walls. The fiber displacement rate during the period of constant temperature is high at hot temperature compare to cold temperature because of the difference in the rate of relaxation for hot and cold temperatures.
 - A mechanism that involves changes in the frictional forces as a function of time within the temperature cycle was used to explain the expansion and shrinkage in the adhesive.
 - Optical coupling method is developed for determining the optical performance of laser diode to fiber alignment with temperature and time. In analytical calculation for optical coupling efficiency the finite element data for the fiber displacement was used to determine the optical coupling behavior of the module.
 - The fluctuation width of the optical coupling efficiency (for hot and cold temperature) increases with the number of thermal cycles. It is also found that the fluctuation width depends on the initial coupling efficiency of the optical modules. Coupling efficiency variation at the end of 100th cycle is of less than 2% (23% to 24.94%) for the 25 % initial coupling efficiency compare to 7% (86.5% to 93.74%) for the 94% initial.
 - Optical coupling efficiency of the assembled module was measured after 100 cycles and it is comparable with the analytically determined value. Final

degradation of less than 3% in final optical coupling was observed for the optical modules. Fluctuation of the optical output value during a given cycle could vary up to 7%.

In this research projects, low cost optical module using the passive alignment technology and polymer materials is designed and fabricated successfully, and its optical reliability is studied in detail. To summarize, there is a convincing case for the use of passive alignment and polymeric materials for the optical modules. These factors will help in the introduction of commercial optical modules at costs competitive with those for copper links.

7.2 Future work

Finite Element Modeling and Optical Simulation:

- The FEA based model implemented in this research work can be further improved by developing rigorous models based on similar concepts, considering other important parameters such as curing effects, humidity, and plastic properties of the adhesives [132]. Curing of the adhesive can bring initial misalignment and residual stress in the optical modules. Both of these effects are problematic for the optical as well as mechanical reliability of the modules. Humidity brings a lot of changes (mechanical and chemical both) in the polymers and thus it is necessary to include it in the simulation to complete the reliability study of the optical transceivers based on the polymer materials. Plastic property of polymers is investigated in detail by many researchers and adding it to this work will bring completeness to reliability study of the optical modules.
- Finite-element method should be combined with the optical analytical method to directly determine the effect of the different parameters on the optical performance of the transceiver. It will help in keeping direct track of the changes in coupling efficiency of the modules with change in FEA parameters like dimensional change of the modules, loading conditions and environmental effects.

- Optical simulation for the complete module should be enhanced by including the wave nature of optical beam and optical aberration of optical components [3-5]. Wave property of optical beam is important because of the diffraction property, which can not be considered using ray optics.

Improvement in Optical Modules

- Instead of using Si as assembly platform, one should introduce polymer platform. Polymer waveguide or polymer optical fiber is available. It is good to assemble a fully polymer based optical modules, which will reduce the cost and weigh of the device. It will also avoid the materials mismatch and enhance the thermal-mechanical stability of the optical modules.
- Development of optical adhesive materials with superior thermo-mechanical as well as optical properties. It is more important that the materials properties should not degrade for long term to make the optical module function properly.
- Microlens along with index matching gel can be introduced wherever optical alignment is required to match the mode of incoming laser beam at optical fiber input. UV-curable adhesives are quite promising for the optical devices in sense that curing process is fast which help in avoiding the initial misalignment. Thus, UV-curing optical adhesive should be used to attach the lens. Adding a new element (in this case lens) will bring more complexity in the system. Hence, the reliability of system should be studied for the new system using the method purposed in this study.
- Most important thing to consider for the future development is Integrated Optics circuits [133]. Analogous to how electrical ICs has benefited society it is hoped that optical integration will also result in a similar revolution in the state of technology. As in all forms of integration it is expected to have size reduction, increase in density, simplification of assembly and packaging, an enhancement of robustness, a removal of parasitic, an improvement in speed and possibly a reduction in cost. True integrated semiconductor optics takes advantage of batch fabrication inherent to semiconductor processing to yield an integrated optical micro system on a chip. The capabilities of this “laser beam circuitry”, as integrated optics was originally conceived, have grown from the clever use of

guided wave structures and discrete devices to the point where complete optical circuits on a single piece of semiconductor may now be fabricated. There basically two approaches when trying to fabricate a semiconductor based integrated optical circuit. The first is monolithic integration [134] and the other is Hybrid integration [135].

Publications (on PhD Research Work)

Patent

1. Anand K. Asundi, **A. Priyadarshi**, and S.G. Mhaisalkar, “Moiré Interferometric Strain Sensor (MISS),” USA Patent under review.

Journal Papers

1. **A. Priyadarshi**, L.H. Fen, Anand K. Asundi, S.G. Mhaisalkar, P.V. Ramana and V. Kripesh (2006) “Misalignment of the optical fibers in multi-channel V-grooves,” Thin Solid Films, Volume 504 ,pp. 341-345
2. **A. Priyadarshi**, L. Hsueh Fen, S. G. Mhaisalkar, V. Kripesh, Anand K. Asundi (2006) “An Investigation of Fiber Misalignment in silicon V-groove Based Optical Modules due to Thermal Excursion,” Optical Fiber Technology, Volume 12, No. 2, pp. 170-184
3. **A.Priyadarshi**, L. Shimin, EE Hua, R. Rajoo, S. G. Mhaisalkar, V.Kripesh (2005) “Refractive Indices variation with temperature and humidity of Optical Adhesive,” Accepted in Journal of Electronics Materials, Journal of Electronic Materials, Vol. 34, No. 11, pp. 1378-1384
4. **A. Priyadarshi**, Lim Shimin, S. G. Mhaisalkar, Ranjan Rajoo, EE Hua, V.Kripesh, E. B. Namdas (2005) “Optical Properties Characterization of Acrylate based Adhesive with temperature,” Journal of Applied Polymers, Vol. 98, pp. 950–956
5. **A.Priyadarshi**, P.V. Ramana, S. G. Mhaisalkar, V. Kripesh, Qingxin Zhang and Anand K. Asundi (2005) “Optical Coupling Efficiency Studies of Passively Aligned CWDM Optical Modules” Optics Communications, Vol. 248, pp.191–199
6. **A.Priyadarshi**, S. G. Mhaisalkar, V. Kripesh, and Anand K. Asundi, “Optical Reliability of single mode Passively Aligned Optical Modules for Temperature Cycle” Under Review.
7. **A.Priyadarshi**, Anand K. Asundi, V. Kripesh, and S. G. Mhaisalkar “Moiré Interferometric Strain Sensor (MISS)” Under Review.

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1. **A. Priyadarshi**, H. Kaur, Anand K. Asundi, S. G. Mhaisalkar, V. Kripesh (2005) "Effect of humidity on optical fiber-adhesive bonding." SPIE conference on Optical Manufacturing and Testing VI, 31 July - 4 August at San Diego (USA)
2. **A. Priyadarshi**, L. Hsueh Fen, Anand K. Asundi, S. G. Mhaisalkar, V. Kripesh (2005) "Misalignment of the Fiber in Multi-Channel V-grooves for Optical Module Packaging," 3rd ICMAT, 3 – 8 July at Singapore
3. Lim Shimin, **A. Priyadarshi**, Ranjan Rajoo, E. H. Wong, S. G. Mhaisalkar, V. Kripesh (2005) "Methodology to Study the Effect of Moisture on Refractive Index of Optical Adhesive", Proc. SPIE Vol. 5852 Singapore, pp. 339-344
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Appendix A: 2-D model to calculate the fiber displacement

```
FINISH
/CLEAR
/CONFIG,NRES,10000
/FILENAME,2D_OPTICAL_FIBER DISPLACEMENT
/TITLE, SAMPLE 1
*AFUN,DEG
! DEFINING VARIABLES
SIOB_WIDTH= 1900
SIOB_HEIGHT= 649
V_WIDTH =195
LEFT_CORN = 54
LEFT_GAP = 26
RAD_CLAD =62.5

!PREPROCESSING
/PREP7
*AFUN,DEG

! SIOB DRAWING
K,1,0,0
K,2,0,SIOB_HEIGHT
K,3,(SIOB_WIDTH-V_WIDTH)/2,SIOB_HEIGHT
K,4,SIOB_WIDTH/2,SIOB_HEIGHT - (V_WIDTH*TAN(54.7)/2)
K,5, (SIOB_WIDTH+V_WIDTH)/2,SIOB_HEIGHT
K,6,SIOB_WIDTH,SIOB_HEIGHT
K,7,SIOB_WIDTH,0
A,1,2,3,4,5,6,7

! FIBER DRAWING
```

```
K,10, ((SIOB_WIDTH-V_WIDTH)/2)+(LEFT_CORN*COS(54.7)),SIOB_HEIGHT -  
LEFT_CORN*SIN(54.7)  
KWPAVE,10  
CSYS,4  
WPROTA,90-54.7  
K,11,RAD_CLAD+LEFT_GAP  
CSYS,0  
WPROTA,54.7-90  
KWPAVE,11  
CYL4, 0,0,62.5
```

! ADHESIVE DRAWING

```
KWPAVE,11  
CSYS,4  
K,20,-10,-1500          !1500 IS ARBITRARY NUMBER FOR GETTING THE  
ADHESIVE CURVATURE  
CSYS,0  
KWPAVE,20  
CYL4,0,0,1750,50,,130  
ASBA,3,1,,,KEEP  
ADELE,4,6,1,1  
ASBA,7,2,,,KEEP  
WPAVE,0,0  
!  
AGLUE, ALL
```

! MATERIALS PROPERTIES ASSIGNMENT

```
ET,1,PLANE82,,,2          !ELASTIC 8 NODE ELEMENT  
ET,2,VISCO88,,,2         !VISCOELASTIC 8NODE ELEMENT
```


! MATERIAL PROPERTIES OF SILICON SUBSTRATE

MP,KXX,1,160
MP,EX,1,0.137
MP,PRXY,1,0.26
MPTEMP,1,-65+273,25+273,65+273,100+273,150+273,200+273,280+273)
MPDATA,ALPX,1,1,2.25E-6, 2.25E-6, 2.25E-6, 2.25E-6,3.8E-6, 3.8E-6,4.8E-6

/COM MATERIAL PROPERTIES OF OPTICAL FIBER

MP,KXX,2,2.9
MP,EX,2,0.08
MP,PRXY,2,0.23
MP,ALPX,2,0.55E-6

/COM MATERIAL PROPERTIES OF ADHESIVE (VISCOELASTIC)

TB, EVISC, 100
TBDATA, 1, 5.311 !WLF CONSTANT C1
TBDATA, 2, 81.35 !WLF CONSTANT C2IN KELVIN
TBDATA, 4, 343.3 !REFERENCE TEMPERATURE
TBDATA, 5, 1 !WLF
TBDATA,26,120E-6 !THERMAL EXPANSIONCOEFFICIENT IN RUBBER
STATE
TBDATA,31,60E-6 ! THERMAL EXPANSIONCOEFFICIENT IN GLASS
STATE
TBDATA, 46, 2.55E-4 !SHEAR MODULUS AT TIME = 0
TBDATA, 47, 1E-8 !SHEAR MODULUS AT TIME = INFINITY
TBDATA, 48, 7.65E-4 !BULK MODULUS AT TIME = 0
TBDATA, 49, 1E-8 !BULK MODULUS AT TIME = INFINITY
TBDATA,50,7 !SEVEN SHEAR RELAXTION
TBDATA,51, 0.0607 !COEFFICIENTS FOR SHEAR MODULUS
RELAXATION USING
TBDATA,52,0.4123 ! 7 MAXWELL ELEMENTS

```
TBDATA,53,0.3391
TBDATA,54,0.1554
TBDATA,55,0.0279
TBDATA,56,0.003
TBDATA,57,0.0018
TBDATA,60,3.2E-8      !RELAXATION TIMES FOR SHEAR MODULUS
RELAXATION SEVEN USING
TBDATA,61,2.6E-6      !MAXWELL ELEMENTS
TBDATA,62,2.14E-4
TBDATA,63,0.018
TBDATA,64,1.507
TBDATA,65,124.451
TBDATA,66,10400
TBDATA,71,0           !ZERO MAXWELL ELEMENTS BULK MODULUS
RELAXATION
MP, DENS, 100, 1
!
! ASSIGNING ATTRIBUTE TO THE DIFFERENT PART OF MODEL
ASEL,S,AREA,,4
AATT,1,,1,0
ASEL,S,AREA,,2
AATT,2,,1,0
ASEL,S,AREA,,3
AATT,100,,2,0
ASEL,ALL
!
! MESHING
SMRTSIZE,1
MSHAPE,0,2D
MSHKEY,0
AMESH,ALL
```

! REFINING THE MESH AROUND SILICON-ADHESIVE-FIBER JOINT

LREFINE,3,4,1,2,2

LREFINE,8,11,1,2,2

! APPLY CONSTRAINT IN X AND Y DIRECTION ON MODEL

LSEL,S,LINE,,7

DL,ALL,,UY,0 **!MAKE Y MOVEMENT = 0,**

LSEL,ALL

NSEL,S,,,1 **! CONSTRAINT IN X AND Y DIRECTION FOR THE LEFT
CORNER**

D,ALL,UX,0

D,ALL,UY,0

NSEL,ALL

FINISH

! START SOLUTION

! DEFINE TEMPERATURE LOADING AND SOLVE THE PROBLEM

/SOLU

SOLCONTROL,0

ANTYPE,STATIC

NLGEOM,ON

OUTRES,ESOL, 1

TREF,25+273.3

TOFFST,273

STARTTEMP=25+273.3

HIGHTEMP=85+273.3

LOWTEMP=-40+273.3

RAMPRATE=5

T1=300 !5MINTS RAMPING

SECTIME=900 !15MINTS HOLD

!----- SET INITIAL CONDITIONS -----

TUNIF,STARTTEMP

TIME,1E-5

CNVTOL,F,,,0.00001

SOLVE

!----- LOAD STEP THERMAL CYCLES -----

OUTRES,ESOL,1

N1=0

N2=0

*DO, I, 1, 100

NSUBST, 5

TUNIF, LOWTEMP

N1=N1+1

TIME, (T1*N1)+(SECTIME*N2)

SOLVE

NSUBST, 10

N2=N2+1

TIME, (T1*N1)+(SECTIME*N2)

SOLVE

NSUBST, 5

TUNIF, HIGHTEMP

N1=N1+1

TIME, (T1*N1)+(SECTIME*N2)

SOLVE

NSUBST,10

```
N2=N2+1
TIME, (T1*N1)+(SECTIME*N2)
SOLVE
*ENDDO
FINISH
```

! Post processing

```
/OUTPUT
/POST26
ESOL,1,3638,,BFE,nodTEMPR
NSOL,2,7638,u,X,Xdisp
NSOL,3,7638,u,y,ydisp
ESOL,4,3002,,S, x, EQV 7
ESOL,5,2061,,S, x, EQV 2
ESOL,6,1469,,S, x, EQV 3
ESOL,8,3054,,S, X, EQV 4
ESOL,9,3030,,S, X, EQV 5
ESOL,10,3462,,S, X, EQV 6
!PLOTING RESULTS.
XVAR,2
/GRID,1
/AXLAB, X, TEMPERATURE
/AXLAB,Y,DISPLACEMENT (MICROMETER)
PLVAR,2,3,4,
NSTORE,1          ! STORE EVERY 20TH TIME POINT RESULTS
! LISTING THE STORED RESULTS
PRVAR,3,4,5,6,7
PRVAR,8,9,10
FINISH
```