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Optical Fiber Fusion Splicing

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Andrew D. Yablon

Optical Fiber Fusion Splicing

With 137 Figures

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Dr. Andrew D. Yablon
OFS Laboratories
19 Schoolhouse Road
Somerset, NJ 08873
USA
E-mail: ayablon@ofsoptics.com

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2. Fiber Preparation and Alignment

As we learned in Chap. 1, optical fiber fusion splicing is comprised of many steps aside from heating the fiber tips to form a welded joint. Prior to actually forming a joint, the fiber tips must be specially prepared. Nearly all silica optical fibers are coated with a protective polymer material that must be removed, or *stripped*, prior to fusion splicing. Following stripping, the fiber tips must be *cleaved* in order to obtain planar end faces suitable for fusion splicing. These preparatory steps are usually performed by instruments separate from the fusion splicer that actually forms the splice joint. Once the tips are prepared, they must be *aligned* to each other in preparation for joint formation. Over the past three decades, both fiber preparation and fiber alignment have evolved along with optical fibers themselves.

One might assume that fiber preparation for fusion splicing is relatively unimportant compared to the actual joint formation, loss estimation, or splice packaging. Previous treatments of optical fiber fusion splicing have indeed overlooked fiber preparation. However, certain aspects of fiber preparation are of critical importance since they significantly impact both the optical quality and the long-term reliability of the resulting fusion splice. For example, the cleave quality is a major contributor to geometric deformation in a fusion splice, and this geometric deformation is often a dominant factor controlling the splice loss (see Chaps. 4 and 5). The stripping process is often the dominant factor controlling the ultimate tensile strength of the resulting splice, which in turn determines the long-term reliability of the splice (see Chap. 6).

In this chapter we present a general introduction to optical fiber stripping, cleaving, and alignment technology applied to fusion splicing. More specific information is available in the numerous references cited throughout the chapter.

2.1 Stripping

The fundamental motivation for stripping the coating from a fiber prior to fusion splicing is that the high temperatures experienced during joint formation will damage polymer coatings and possibly damage the heated portion of glass contacting the coating. Furthermore, alignment of the fiber is more accurate when gripping on the bare glass surface because the dimensional tolerances of the glass are usually far superior to that of the polymer coating. Finally, optical fiber coatings often exhibit shape memory, known as *curl*, which can complicate fiber alignment (see Sect. 3.2.1).

However, the stripping process can reduce the fiber's mechanical strength and long-term reliability by degrading the pristine glass surface [2.1, 2.2]. Furthermore, bare silica fiber can easily incur new strength-reducing surface flaws. Finally, any splice package or protector must be at least as long as the length of stripped fiber. For these reasons, fusion splicers are designed to work with a minimum length of stripped fiber, which typically ranges from about 5 mm to about 20 mm when measured from the cleaved tip.

The ultimate tensile strength of a fusion splice is closely correlated with its long term mechanical reliability (see Chap. 6), and this tensile strength is often directly determined by the details of the stripping process. The ultimate tensile strength of as-drawn, coated, 125 μm diameter fiber is about 57 N, which is equivalent to about 5.5 GPa or 800 kpsi (kpsi stands for kilopounds force per square inch, a common industry unit) of tensile stress. Stripping can reduce this tensile strength by as much as, and sometimes even more than, an order of magnitude. Furthermore, any coating residue left on the glass fiber's surface can interact with the heated fiber during joint formation leading to significantly lower tensile strength and reduced long term reliability.

Coating removal technologies can be broadly organized into three categories: (1) mechanical and thermo-mechanical stripping, (2) chemical stripping, and (3) vaporization techniques (which include laser- and flame-based techniques). Generally speaking, chemical and vaporization techniques are essential for high-strength fusion splices. However, they also require more expensive and more complicated hardware, and may pose serious safety hazards. Thus, most field splicing, and a good deal of laboratory and factory splicing, is performed with the aid of mechanical and thermo-mechanical stripping. As more production fusion splicing is automated, chemical, and especially vaporization techniques are becoming more common.

In this section we will provide an introduction to optical fiber stripping for fusion splicing. We begin our treatment with a discussion of common optical fiber coating designs. We then discuss each of the three major categories of stripping. For the interested reader, a comprehensive and up-to-date review of optical fiber cable construction and coating removal is available in [2.3].

2.1.1 Fiber Coatings

An analysis of the stripping process requires an understanding of the optical fiber coating itself. An optical fiber's coating design obviously depends on the fiber's application. For example, connectorized optical fiber cable jumpers and patchcords are typically endowed with several robust polymer layers, as well as a Kevlar yarn layer, to endure frequent handling. In contrast, a specialty fiber, such as erbium-doped fiber (EDF), is usually not designed to withstand much handling or environmental stress, so it is typically available as a single strand with only a soft 250 micron diameter acrylate coating. Ribbon fiber consists of several individual coated fiber strands held together in a linear arrangement by a soft polymer binder. Some specialty multimode fibers have pure silica cores directly coated with a low refractive index polymer that also serves as the optical cladding.

Despite this wide variety, coatings of fibers designed for fusion splicing share some common features. The innermost polymer coating is nearly always a relatively soft, UV-cured, urethane acrylate, which exhibits a refractive index higher than that of silica in order to strip out and attenuate unwanted light. This acrylate coating consists of one or two distinct layers (Fig. 2.1). If there are two layers, the inner acrylate layer, known as the *primary* coating, is very soft in order to minimize microbend losses [2.3, 2.4], and has an outer diameter of about 180 μm. The outer layer, known as the *secondary* coating, is a harder acrylate, thus providing better abrasion resistance. The outer diameter of the entire acrylate coated fiber is usually 250 μm, although specialty fiber coatings can be as large as 400 μm. When the glass fiber itself is only 80 μm in diameter, the outer diameter of the acrylate coated fiber is also smaller, often on the order of only 150 μm.

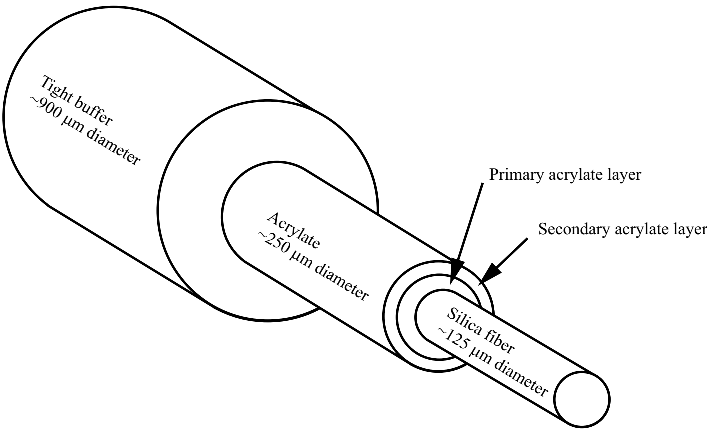

Fig. 2.1. Schematic illustration of typical polymer coating architecture for single stranded fiber. Figure not to scale

The individual strands comprising a ribbon fiber are also usually coated with a dual acrylate layer, and the strands are bonded together by an acrylate polymer matrix (Fig. 2.2). These relatively soft polymer materials facilitate the stripping process.

In addition to the innermost coating layers, some fibers have additional layers of polymer, termed *buffer* layers. One common additional layer is the *tight buffer*, which can exhibit an outer diameter ranging from 500 to 1000 μm

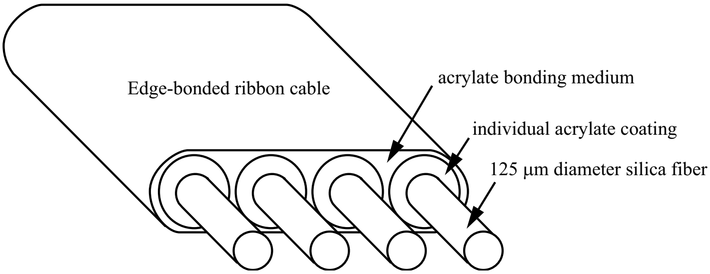

Fig. 2.2. Schematic illustration of an edge-bonded ribbon fiber. After [2.3]

but is usually 900 μm. Tight buffer coating is a hard plastic (much harder than acrylate) that tightly grips the underlying acrylate and usually must be removed in conjunction with the acrylate underneath. As its name suggests, *loose buffer* differs from tight buffer in that it does not tightly grip the underlying acrylate layers, so it can be removed without damaging the underlying acrylate.

Optical fiber coatings are often color coded to facilitate identification. This is especially true in ribbon fiber cables. The coloring agent in the coating usually does not affect the stripping process, but in some cases, such as when TiO_2 is used as a coloring agent and chemical stripping is performed, stripping conditions must be modified to maintain high tensile strength [2.5].

One alternative to the usual acrylate coatings is a single layer of only 10 μm of polyimide coating. Polyimide is attractive for some extreme applications because of its stability at high temperature. Some polyimide coated fibers can withstand temperatures as high as 300° C for long periods of time and 400° C for short durations. However, polyimide coatings are much more difficult to remove, and are generally only found on certain specialty fibers.

Some large diameter (200 μm or more) multimode silica fibers are coated with a hard, low refractive index polymer, which can serve as both a coating and an optical cladding. The coatings of these *hard clad silica* fibers, commercially known as *HCS*^{TM} or *TECS*^{TM}, improves fiber strength and abrasion resistance so these fibers can often be cabled without Kevlar yarn. Moreover, connectors can usually be mechanically attached directly to the hard coating, facilitating connectorization. Like polyimide coatings, hard plastic coatings are difficult to remove so these fibers are usually intended to be connectorized, rather than fusion spliced.

Individual coated transmission fibers are often packaged into cables, which often exhibit a complex architecture and can include hundreds of individual fiber strands. The interested reader is referred to [2.3, 2.6, 2.7] for a detailed treatment of such transmission cables, and how they are prepared for splicing.

Some specialty silica fibers are fabricated with a thin layer of amorphous or crystalline carbon on the outer surface of the glass cladding just underneath the innermost polymer coating [2.3, 2.8]. This carbon layer is called a *hermetic* coating since it is designed to prevent hydrogen or water molecules from diffusing into the fiber from the ambient environment. These hermetic coatings have been shown to improve the mechanical fatigue characteristics of optical fibers. Hermetic carbon coatings cannot be removed by mechanical means. However, heating the fiber to a high temperature can remove the carbon coating and the very high temperatures experienced during fusion splicing will naturally remove the carbon coating in the vicinity of the fusion splice and therefore also permit visualization of the fiber core and loss estimation [2.8].

2.1.2 Mechanical and Thermo-Mechanical Stripping Techniques

Mechanical and thermo-mechanical techniques are by far the most commonly employed methods to strip the coating from optical fiber in preparation for fusion splicing. These techniques are inexpensive, fast, and applicable to a fairly wide variety of coating designs (with the notable exception of polyimide and hard clad silica). Both mechanical and thermo-mechanical stripping can be performed with relatively inexpensive hand-held tools. Nearly all field splicing utilizes mechanical or thermo-mechanical stripping. A large segment of factory or laboratory fusion splices are also prepared with these techniques.

As their names suggest, mechanical and thermo-mechanical stripping involve cutting into the coating with a hard tool to fracture the coating, and then translating the tool along the fiber to peel the coating from the fiber and push it off the surface [2.4]. When the coating is relatively rigid, the coating will delaminate from the glass fiber's surface. When the coating is made from a softer polymer, such as the primary coating of a dual acrylate coating, it may leave a residue of coating adhering to the glass fiber's surface. Generally speaking, dual acrylate coatings require less force to mechanically or thermo-mechanically strip the fiber than single acrylate coatings [2.4].

Many mechanical fiber stripping tools closely resemble wire stripping tools, and share the same principle of operation (Fig. 2.3). The initially coated fiber is usually pulled through a tiny aperture, which contains sharp surfaces that cut through the coating. Unlike in a conventional wire stripping tool, the aperture in a optical fiber stripping tool is carefully designed to minimize the possibility that it will contact the vulnerable glass surface and damage it. Conventional wire stripping tools *cannot* be used to strip optical fiber as they will scratch the glass surface making the fiber fragile.

Thermo-mechanical stripping is a variant of mechanical stripping in which an electric heater softens the polymer coating to facilitate removal. The heat from a thermo-mechanical stripping tool can also help to straighten a fiber exhibiting a large amount of coating curl. Thermo-mechanical stripping is particularly attractive when the coating consists of a single acrylate layer. When the fiber has a dual acrylate coating, the softer inner layer is more easily separated from the glass surface, so mechanical stripping usually suffices.

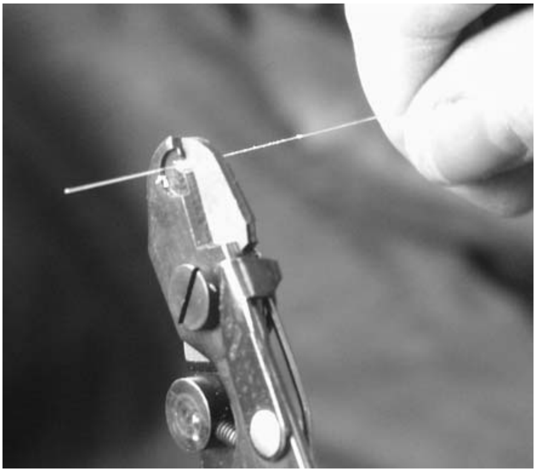

Fig. 2.3. Common optical fiber mechanical stripping tool applied to standard single-mode fiber with a standard 250 μm diameter dual layer acrylate coating

Thermo-mechanical stripping is commonly used to strip ribbon fiber, which is usually designed with a soft, easily stripped acrylate coatings. Even ribbons containing as many as 12 or 24 individual fibers can be stripped down to the bare glass with relatively little force with the aid of a suitable thermo-mechanical stripping tool. However, the tensile force applied to the ribbon cable during thermo-mechanical stripping is proportional to the number of fiber strands in the cable so large forces are required to thermo-mechanically strip 24-fiber ribbon cable [2.9].

In another variant of mechanical stripping that is very similar to chemical stripping, the fiber coating can be briefly soaked in a solvent, such as methylene chloride (also known as dichloromethane or methylene dichloride), which causes the coating to soften and to swell, thus facilitating mechanical stripping [2.10]. However, the need for such a solvent, which may be toxic, makes this variant less convenient and less common than other forms of mechanical stripping.

When the fiber is coated with a tight buffer as well as an acrylate coating, a thermo-mechanical stripper can be used to simultaneously remove the tight buffer and the acrylate coating. The fiber chucks of many commercial fusion splicers are designed to accommodate tight-buffered fiber. Alternatively, special tools employing sharp razor blades can sometimes remove the tight buffer without damaging the underlying acrylate coating.

Mechanical stripping usually leaves some amount of coating residue on the glass surface of the fibers. This results from the fact that the stripping aperture cannot physically contact the glass surface or it would significantly reduce the fiber's mechanical strength. Any coating residue remaining on the fiber can interfere with the fiber chucks, the splicer's image-processing based fiber alignment process, or can be baked into the fiber surface during joint formation, thus weakening the mechanical strength and long term reliability of the resulting splice. Coating residue on the fiber surface should be removed with some kind of cleaning solvent. Organic solvents such as alcohol, acetone, or even methylene chloride are used to wash away coating residue. Ultrasonic agitation of a solvent bath is a common strategy to accelerate residue removal. Alternatively, wiping the fiber with a solvent soaked swab or tissue can effectively remove coating residue, at the expense of introducing surface defects which will significantly reduce the mechanical strength of the resulting splice.

Another significant disadvantage of mechanical or thermo-mechanical stripping is that it will always induce some degradation of the fiber surface thus weakening the fiber's mechanical strength and also its long term reliability. Mechanical and thermo-mechanical strippers are designed to minimize the severity of this effect. When operated properly, a high quality mechanical stripping tool, such as the one depicted in Fig. 2.3, can yield tensile strengths of about 3.5 GPa (500 kpsi) when applied to a standard 250 μm outer diameter dual-acrylate coating on a 125 μm diameter silica fiber. However, this requires skill and careful attenuation to the process.

2.1.3 Chemical Stripping Techniques

Chemical stripping involves the use of an aggressive solvent to remove the polymer coating of the fiber. Chemical stripping is attractive since, unlike mechanical stripping, it does not require mechanical forces that cause defects on the fiber surface leading to strength and reliability degradation. Moreover, chemical stripping is effective for nearly all optical fibers, including polyimide coated and hard clad silica. However, most of the chemicals are toxic, and some are even flammable. Thus chemical stripping does not lend itself to field splicing, but has been frequently employed in the laboratory or factory environments, especially when extremely high tensile strength and mechanical reliability is required. Chemical stripping requires on the order of one minute of processing time, which is longer than mechanical or vaporization stripping techniques.

Sulfuric acid, or a mixture of sulfuric and nitric acid (for example 95% H_2SO_4 and 5% HNO_3 by weight), heated to about 200° C is the most common solvent for chemical stripping [2.5,2.10,2.11]. Hot acid is particularly effective for stripping hard clad silica or polyimide fiber coatings, which are otherwise very difficult to strip. Typical acid baths require about 30 seconds of soaking to completely remove a 250 micron outer diameter acrylate coating from a 125 μm fiber. At lower temperature or at higher pH, the processing time is significantly lengthened. To achieve the best possible stripping performance, the acid must be changed when it becomes heavily contaminated by dissolved coating material [2.1]. Acid stripping poses many serious safety hazards and the working environment must be well ventilated (for example by fume hood) to ensure the safety of the operator.

Some papers have claimed that hot-acid stripping actually degrades the strength of the fiber, but recent work has refuted that claim [2.10]. Soaking a fiber in a clean hot acid bath for long amounts of time (multiple minutes) does not appear to degrade the fiber's mechanical strength [2.10]. In fact, Krause and Kurkjian showed that fusion splices exhibiting no measurable reduction in tensile strength compared to the original as-drawn fiber could be fabricated with acid stripping [2.12].

Methylene chloride (also known as dichloromethane or methylene dichloride) is an alternative to acid for removing acrylate coatings. Several minutes soaking in methylene chloride can soften acrylate coatings to the point that they may be readily peeled off the fiber intact. However, like hot acid, methylene chloride poses serious safety risks as it is a suspected carcinogen and is also flammable. Some solvents, especially methylene chloride, can wick up long lengths of fiber causing the primary coating to separate from the glass.

Although chemical stripping usually leaves no coating residue, a final rinse step is necessary to ensure no solvent remains on the fiber. Depending on the stripping solvent, water, acetone, or alcohol are commonly employed as rinse agents.

2.1.4 Vaporization Stripping Techniques

A number of vaporization stripping techniques have recently been developed and commercialized so they are viable alternatives to chemical and mechanical stripping. In these techniques, the coating material is removed from the fiber by high temperatures. Vaporization techniques are very fast, avoid dangerous solvents, minimize the amount of force applied to the fiber, minimize the amount of coating residue, and often maximize the surface quality of the resulting stripped fiber. However, the hardware required for vaporization-based fiber stripping is substantial, which precludes field splicing applications. Vaporization stripping techniques are well suited to automated splicing applications in a factory setting.

Most fiber coatings are flammable and can actually be removed through combustion in an oxygen atmosphere (including ambient) in a process sometimes termed *flame stripping*. However, burning off the coating significantly reduces the tensile strength of the stripped fiber, to an even greater extent than mechanical stripping. When hot acid is unavailable, a flame or some other high temperature heat source, is the only effective way to remove polyimide or hard clad silica fiber coatings.

Scanning a hot jet of gas over a coated fiber is one of the most common vaporization techniques [2.11, 2.13–2.16]. The temperature of the gas jet is on the order of several hundred degrees Celsius, which is much higher than the maximum temperature the coating can withstand, but still much lower than the softening point of the optical fiber itself. Hot gas jet coating removal has been attributed to explosive thermal stresses in the coating material by one source [2.16] and rapid dehydration by another [2.11]. After the gas jet stripping process (but prior to fusion splicing) the tensile strength of a standard 125 µm diameter fiber has been cited to be on the order of 5 GPa (700 kpsi) [2.11, 2.14, 2.16], which is nearly as strong as the virgin fiber (5.5 GPa or 800 kpsi).

In another technique, termed *thermo-vacuum vaporization* (TVV) [2.17, 2.18] the coating blows off after being heated for a few seconds while held under vacuum. The fiber strengths following TVV are also quite impressive, on the order of 4 GPa (600 kpsi) [2.17] for a standard 125 µm diameter fiber.

Tightly focused laser beams have also been used to remove coating from optical fibers. This type of coating removal process is also termed *laser ablation*. The laser wavelength must be strongly absorbed by the coating to be effective. Frequency doubled copper vapor lasers as well as UV-emitting excimer or far-IR emitting CO_2 lasers have been used to strip coating from optical fiber [2.19–2.21].

2.2 Cleaving

Optical fiber fusion splicing nearly always requires that the fiber tips exhibit a smooth end face that is perpendicular to the fiber axis. A sufficiently perpendicular and planar fiber end face can be achieved via a process termed *cleaving*, in which the brittle glass fiber is fractured in a controlled manner. As we shall see, cleave quality is an important factor controlling fusion splice loss. High quality cleaves are essential when fusion splicing challenging specialty fibers such as erbium-doped fiber (EDF) or dispersion-compensating fiber (DCF).

Polishing a fiber tip can result in even higher quality fiber end faces, but polishing requires more expensive equipment and more processing time, so it is very rarely employed for fusion splicing. However, polishing is commonly used for fabricating optical fiber connectors.

A wide variety of cleaving instruments are now commercially available. Some cleavers are intended for field splicing applications while others are geared for laboratory or factory environments. Some ribbon fiber cleavers can simultaneously cleave all 24 individual optical fibers comprising a high fiber count ribbon [2.9]. Automated fiber preparation systems, including automated fiber cleavers, are now commercially available as well. Cleavers are available for non-standard optical fiber diameters, which can range up to and beyond 1 mm.

Excellent treatments of optical fiber cleaving are available in [2.22–2.24]. The physics of fiber fracture, with an emphasis on mechanical reliability, are discussed in Chap. 6, and especially in Sect. 6.2. In this section we will provide a practical introduction to fiber cleaving for fusion splicing.

2.2.1 Cleaving Techniques and Hardware

An optical fiber is cleaved by applying a sufficiently high tensile stress in the vicinity of a sufficiently large surface crack, which then rapidly expands across the fiber cross section at the sonic velocity. (Fig. 2.4). This idea has many different practical implementations in a variety of commercial cleaving equipment. Some cleavers apply a tensile stress to the fiber while scratching the fiber's surface with a very hard scribing tool, usually a diamond edge. Other designs scratch the fiber surface first, and then apply tensile stress. Some cleavers apply a tensile stress that is uniform across the fiber cross section while others bend the fiber through a tight radius, producing high tensile stresses on the outside of the bend. Cleave tension is commonly specified in grams of force rather than Newtons. A typical high performance cleaver is shown in Fig. 2.5.

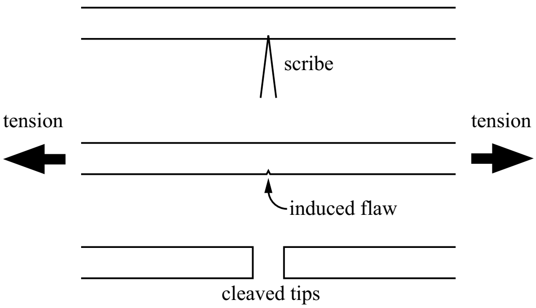

Fig. 2.4. Schematic illustration of scribe-and-tension strategy for cleaving optical fibers

Commercial instruments for simultaneously cleaving all the fibers in a ribbon fiber are also widely available. These ribbon fiber cleavers operate on the same principles as single fiber cleavers. The average cleave quality of a ribbon cleaver is somewhat inferior to that of a single fiber cleaver.

2.2.2 Basic Cleaving Principles

Despite the variation in cleaver design, some basic principles apply to all. The fracture face resulting from a cleave consists of three regions, termed *mirror*, *mist*, and *hackle* [2.22]. These regions are schematically depicted in Fig. 2.6 and photographed in Fig. 2.7a. The mirror zone, which is optically smooth, is produced first as the crack propagates across the fiber. As the crack propagates further away from the initiation site, it forks into multiple crack fronts and hackle results. The hackle is a rough surface that is undesirable for fusion splicing. Mist is the transition region between the mirror zone and the hackle zone.

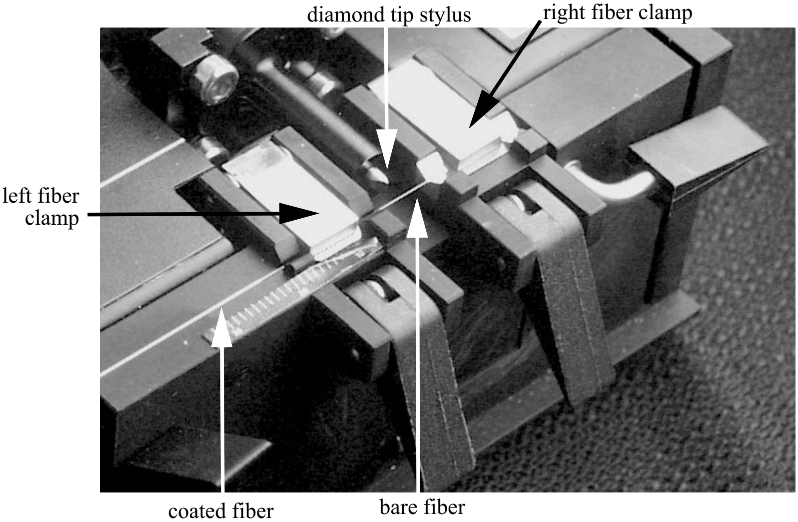

Fig. 2.5. Close-up of the *York FK-11* cleaver which is a typical high performance factory or laboratory optical fiber cleaver. Note the diamond tip stylus which is touched against the tensioned fiber to produce an initial crack which leads to a cleave. Typical cleave angles for this type of cleaver are less than 0.5°

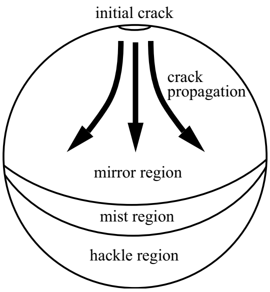

Fig. 2.6. Illustration of different zones associated with cleaving

A high quality optical fiber cleave requires that there be no hackle and minimum mist. The boundary of the mist region is governed by [2.22]

$$\sigma_{\mathrm{a}}^2 D_{\mathrm{mist}} = K_{\mathrm{fract}}^2 \,, \tag{2.1}$$

where σ_{a} is the locally applied tensile stress, D_{mist} is the distance from the crack initiation site to the mist boundary, and K_{fract} is a constant determined by the material. The applied tensile stress, σ_{a}, can be approximated as the cleave tension divided by the fiber's cross sectional area.

The cleave tension must be low enough to ensure that the entire cross sectional area of the fiber falls within the mirror region. When a cleave exhibits hackle, excessive cleave tension may be to blame. However, insufficient

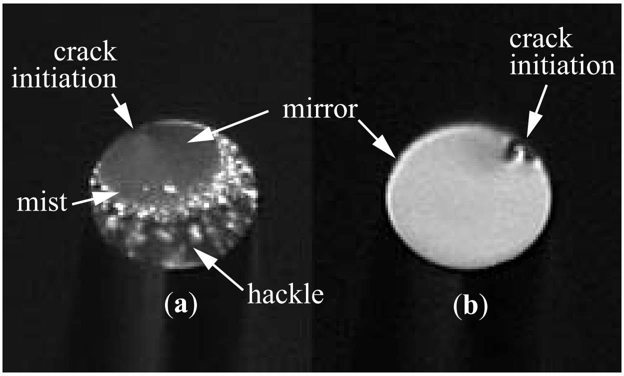

Fig. 2.7. Comparison of two 125 µm diameter cleaved fiber tips viewed with a 0.1 NA 5× microscope objective illuminated obliquely: (**a**) 300 g cleave tension and (**b**) 200 g cleave tension. Note the significant amount of hackle and mist apparent in (**a**) and the nearly complete mirror surface in (**b**)

cleave tension can lead to an angled fiber end face, as discussed in the next Subsection. Furthermore, insufficient cleave tension requires that the initial crack be very large, and this large initial crack may itself comprise a defect in the end face of the final cleaved fiber. The relationship between the stress required to fracture a fiber and the initial crack size is described by crack growth theory and is discussed in Sect. 6.2. Crack growth theory suggests that when a 125 µm diameter fiber is cleaved at a conventional cleave tension of about 200 g force, the initial crack length is on the order of several microns. This is consistent with published studies of initial crack geometry [2.24].

If the distance between the initial crack and mist initiation, D_{mist}, is set equal to the fiber diameter, then (2.1) can be manipulated to show that proper cleave tension approximately scales with the fiber diameter raised to the 3/2 power. If the optimal cleave tension for conventional 125 µm diameter silica fibers is taken to be about 200 g, this scaling law can be used to predict the cleave tension appropriate for other fiber diameters, such 80 µm diameter fibers which require a cleave tension of about 100 g. Figure 2.8 shows how optimal cleave tension varies with silica fiber diameter.

Optical fibers designed to exhibit abrasion resistance are much harder to cleave than regular fibers. The formation of the initial crack during cleaving can be thought of as a form of abrasion. An example of an abrasion resistant fiber is *Corning Titan*^{TM} fiber whose outer cladding is comprised of a TiO_2/SiO_2 glass mixture. One explanation for the difficulty of cleaving this fiber is that the low thermal expansion coefficient of the TiO_2/SiO_2 glass induces residual thermal compressive stresses on the outer surface of the fiber [2.25, 2.26]. Residual compressive stresses on the surface of an optical fiber reduce the amount of tensile stress available for crack growth, thereby inhibiting fracture.

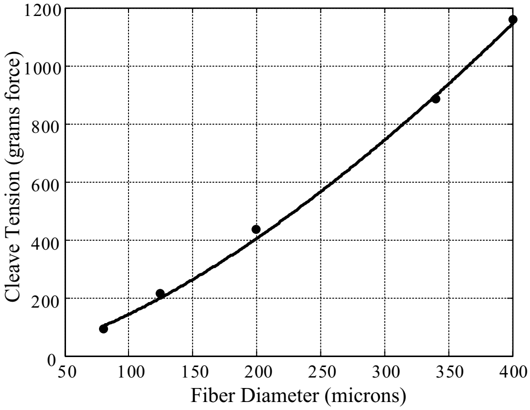

Fig. 2.8. Optimal cleave tension for silica fibers scales with the fiber diameter raised to the 3/2 power. The experimentally observed optimal cleave tensions (*solid circles*) agree with a theoretical prediction based on (2.1). (*solid line*)

Optical fibers with significant amounts of draw-induced residual compressive stress (see Sect. 3.4) on the outer surface of the cladding are also difficult to cleave. For example, fibers drawn at high tension with a low-viscosity glass, such as a heavily fluorine-doped layer, are very difficult to cleave [2.27]. In this case, there will be draw-induced residual compressive stress (see Sect. 3.4) on the outer surface of the fiber that will make it very abrasion resistant and hence difficult to cleave.

2.2.3 Cleave Defects

Since fracture is such a violent and difficult to control process, even the best commercial cleaver will periodically yield defective cleaves. Some common types of cleave defects are depicted in Fig. 2.9. A *lip* (Fig. 2.9a) is a projecting spike of glass at the periphery of the fiber tip. Lips can be a serious problem when they are more than a few microns long, which is enough to interfere with the ability to gap the fibers. Generally a fiber should be re-cleaved when it exhibits a lip that is visible in the magnified image of a fusion splicer.

A *chip* (Fig. 2.9b) is an absent section of glass on the periphery of the cleaved fiber tip. Small chips are often of no consequence. Larger chips represent a deficit of material that will induce surface tension to shear the molten glass at the fiber tip, thus distorting the splice geometry. Cleaved tips exhibiting a chip visible in the magnified image of a fusion splicer should be recleaved.

Any torsion of the fiber during the cleave will result in an *angle* (Fig. 2.9c). This is because a crack will propagate in a direction perpendicular to the local principal tensile stress [2.29, 2.30]. Torsion of the fiber causes the principal stresses of the fiber to be angled with respect to the fiber axis. Angled end

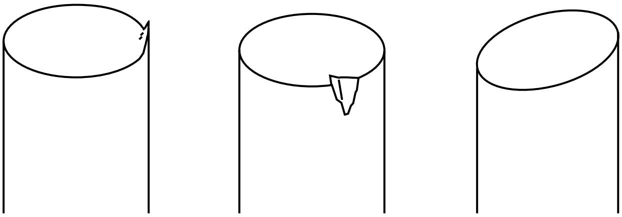

Fig. 2.9. Illustration of three common cleave problems: (**a**) lip, (**b**) chip, (**c**) angle. After [2.23, 2.28]

faces are a clue that the cleaving instrument is inadvertently applying torsion to the fiber; often the fiber clamps are the culprit. Excessively low cleave tension can result in an angled cleave since even small amounts of torsion can significantly alter the direction of the principal stresses. Angled fiber end faces are useful for suppressing reflectance in optical fiber terminations. Fusion splices exhibit such low reflectance (usually less than 60 dB) such that angled cleaves are unnecessary.

Most commercial fusion splice equipment include image processing routines which can measure the end face angle of the fiber tips in two orthogonal axes and abort the splice if the angles exceed a preset threshold. More accurate measurements of fiber end angle, and the topography of the fiber end face, can be performed with an interferometer [2.28]. Convenient, portable hand-held interferometric cleave checkers are commercially available and can be used to measure the discarded portion of the cleaved fiber thus avoiding any contamination of the cleaved fiber tip. Fig. 2.10 depicts some representative interferograms of cleaved fiber tips. When the absolute lowest loss fusion splices are required, cleaved tips can be screened with an interferometric cleave checker.

When a substantial portion of the cross sectional area of an optical fiber is comprised of regions of glass with very different mechanical properties, achieving a defect free end face can be very difficult. This is a common problem with polarization-maintaining (PM) fibers because they typically include large areas of glass with very different mechanical properties and also significant residual stresses. The sonic velocity varies in the different regions so the cleave does not propagate evenly across the end face of the fiber. These issues are discussed in more detail in Sect. 9.2.

2.2.4 The Importance of Cleave Quality

The impact of cleave quality on the quality of the resulting fusion splice should not be underestimated. Deficiencies in a fiber cleave are one of the most common causes for geometric deformation in the resulting splice, which are particularly onerous for single-mode fiber. Much of the variation in splice

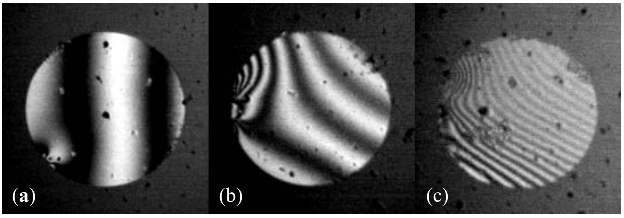

Fig. 2.10. Interferograms of 125 μm diameter optical fiber cleaves obtained using the handheld *Norland Cleave-Chek Interferometer*. (**a**) High quality cleave with an end angle of about 0.3°. The cleave initiation site is visible on the bottom left edge of the fiber. (**b**) More typical cleave with an end angle of about 0.5°. The cleave initiation cite is visible on the left edge of the fiber, as is a small chip on the fiber end face. (**c**) Poor quality cleave with an end angle greater than 2°. Dirt on the reference optical flat is visible in all three interferograms. The operating wavelength of this interferometer is about 650 nm so each degree of end face angle corresponds to about 7 fringes

loss observed between different splices fabricated using the same splice parameters is due to variation in cleave quality.

There are several ways in which a poor cleave can reduce the quality of the resulting splice. It can compromise the performance of image processing routines that perform fiber alignment. Cracks in the fiber's end face (Fig. 9.3) can lead to a bubbles at the splice joint, which usually requires the splice to be remade.

Furthermore, if the end face of the opposing fiber tips are angled with respect to each other, there will usually be a deficit of glass material when the fibers are brought together during the hot push. This deficit of material typically induces shearing of the molten glass, resulting in significant core deformation (Fig. 2.11). One way to reduce the deleterious effects of excessive cleave angles when splicing standard single-mode fiber (SMF) is to use relatively long heating times which encourages surface tension to minimize core deformation [2.31]. However, this strategy is less effective on specialty fibers such as erbium-doped fiber (EDF) or dispersion-compensating fiber (DCF).

Determining a threshold cleave quality for a given fusion splice depends on the fiber designs, the splicing equipment, and the loss requirements. For standard single strand single-mode fiber, typical cleave quality requirements are end face angles less than 1° with minimal lips or chips [2.31, 2.32]. Since cleaving ribbon fiber is more challenging, the maximum cleave angle is often specified to be on the order of 3 or 4° [2.32]. High quality low-loss fusion splices of single-mode fiber, especially fiber exhibiting a small mode field diameter (MFD), will generally require a tighter specification of 0.5°. However, if the cleave requirements are too severe, the cleave yield will be very low and an individual splice will require excessive time to fabricate.

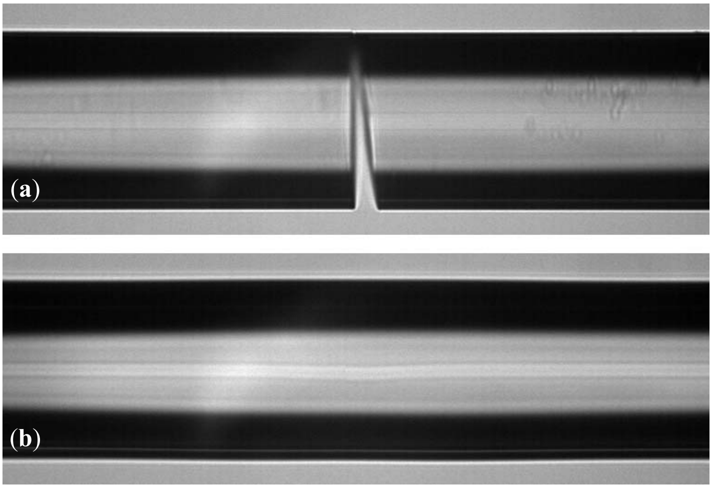

Fig. 2.11. Illustration of the effect of cleave quality on an optical fiber fusion splice showing two fiber tips (**a**) before splice during alignment and (**b**) after splice. The cleave angle of the right fiber tip was about $5°$. The geometric deformation of the core evident in the figure induced about 0.25 dB loss at 1550 nm

2.3 Alignment

Once the fiber tips have been prepared, they must be accurately aligned to each other so that the resulting fusion splice exhibits optimal optical performance, which is commonly defined as low loss and minimal reflectance. As we shall see in this section, several strategies are available for aligning optical fibers.

In the earliest days of optical fiber technology, single-mode fibers were considered to be of questionable value since aligning two $10\,\mu$m diameter fiber cores to form a joint was thought to be too difficult. These concerns were quickly dispelled by the first generation of optical fiber fusion splicing equipment.

Most modern fusion splicers grip the optical fiber tips within some form of v-groove. These v-grooves may grip onto the stripped portion of glass, or onto the polymer coating. Gripping on the glass can permit a more precise alignment than gripping on the polymer coating since the glass usually exhibits less curl and is not compliant. On the other hand, gripping on the glass can induce surface defects that reduce the tensile strength and hence the long-term reliability of the fusion splice (Chap. 6). Normally the axes of the v-grooves are parallel to each other, but a high quality optical fiber fusion splice usually requires that the fiber tips be actively aligned to each other. This alignment normally occurs in the two orthogonal transverse axes. In addition, specialty fibers such as polarization-maintaining (PM) fiber and microstructured fiber require rotational alignment as well (Chap. 9). It is important to note that surface tension effects can significantly alter fiber alignment, as discussed in Sect. 3.2.

In this section we will survey both passive and active strategies for aligning optical fibers in preparation for fusion splicing. The specific details of these alignment strategies depend on related topics, such as the optics of fusion splices, splice loss measurement, and fiber imaging, which are discussed in Chaps. 4, 5, and 7 respectively.

2.3.1 Passive Alignment

The simplest fiber alignment strategy is termed *passive alignment*, and as its name suggests, it requires no active intervention by the operator or the fusion splicer. A passively aligned fusion splice relies on the accurate pre-alignment of fiber v-grooves that grip the outer surface of the fiber tips. The advantages of passive alignment include extremely low cost, simplicity, and speed.

However, passive fiber alignment is characterized by several important disadvantages. Passive fiber alignment requires the fiber tips to exhibit extremely low core eccentricity, low curl, and a well controlled cladding diameter. Passive fiber alignment is less effective when the fiber core diameter is very small, since such fibers are more sensitive to small core misalignments. Passive alignment will not function properly when either the v-groove or the fiber surface is contaminated by dirt.

For these reasons, passive alignment is only found on earlier generation fusion splicing machines or on lower cost field fusion splicers or mass fusion splicers. Nearly all contemporary optical fiber fusion splicers employ some form of active alignment.

2.3.2 Image-Based Active Fiber Alignment

The most common strategy for performing fiber alignment is image-based active fiber alignment in which a microprocessor activates fiber positioners based on a digital image of the fiber tips obtained with the aid of an imaging system comprised of an illumination source, a microscope objective, and a digitizing camera [2.33–2.36] (see Fig. 5.2 and Sect. 5.1). Such an alignment system is obviously more expensive and complex than a passive alignment system, but it is much more powerful and flexible, capable of compensating for small amounts of fiber curl, core eccentricity, dirty fibers or v-grooves, and cladding diameter variations. Moreover, as we shall see in Chap. 5, the same imaging system used for fiber alignment can serve as the basis for loss estimation of the completed splice.

Image-based active fiber alignment systems can align the fiber tips based on the fiber cladding position. Many fusion splices can even use the image of the fiber cores to align the fiber tips. This is termed a *profile alignment system (PAS)* since it aligns the fiber tips based on their refractive index profiles.

However, as we shall learn in Sect. 3.2.3, surface tension effects during fusion splicing can corrupt fiber alignment based on the detected core position.

Contemporary mass fusion splicing systems commonly use image-based active fiber alignment. However, the alignment system does not actively align each individual fiber strand comprising the ribbon. Instead, the individual fiber strands comprising a ribbon are gripped in a substrate containing fixed v-grooves. The two opposing substrates are actively aligned with each other based on the averaged position of the detected fiber claddings (Fig. 2.12). Since this scheme depends on the fiber cladding for alignment, core concentricity and cladding diameter stability can have an important impact on the resulting fusion splice loss.

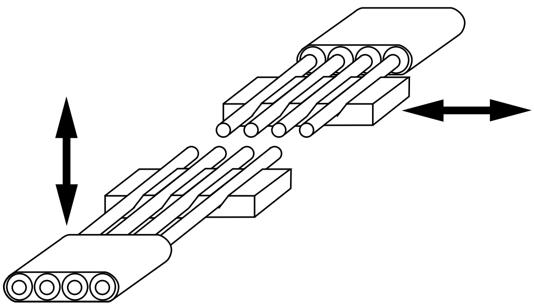

Fig. 2.12. Schematic illustration of a common mass fusion splicer alignment scheme. All the strands of a ribbon fiber tip are simultaneously gripped by fixed v-grooves in a substrate. The two opposing substrates are aligned to each other in two orthogonal axes (indicated by the heavy arrows) by micropositioners. Typically an image-based active alignment system detects the surface of each fiber's cladding and actively aligns the two substrates by minimizing the average cladding misalignment of the individual fiber strands. For the sake of clarity, the figure depicts a ribbon cable with only four fibers, but contemporary ribbon fibers consist of as many as 24 individual fiber strands

Polarization-maintaining (PM) are not rotationally symmetric so high quality fusion splices involving these fibers usually require that the two fiber tips be rotationally aligned to each other. This type of alignment is nearly always performed using image-based alignment systems. Most equipment aligns these fibers based on transverse images but some equipment can align these fiber tips based on endview images of their cleaved end faces. Issues concerning PM fiber alignment are discussed in Sect. 9.2.

2.3.3 Transmitted-Power Based Active Fiber Alignment

Instead of relying on CCD images of the fiber tips, the fiber tips can be actively aligned by monitoring the amount of optical power transmitted across a small air gap (Fig. 2.13). Transmitted-power based active alignment inherently involves a measurement of optical loss, which is described in greater detail in Chap. 7.

Active alignment systems include an optical source, such as a laser diode (LD) or a light-emitting diode (LED), that is coupled into the free end of one fiber, and an optical power meter that detects the amount of power emitted by the free end of the other fiber. A microprocessor programmed with an appropriate algorithm moves the fiber positioners to the location of maximum transmitted power, which is assumed to be the optimal fiber alignment. Unfortunately, active alignment can lead to alignment errors resulting from imperfect cleave angles, which refract the light as it traverses the air gap between the fiber tips so that the alignment with maximum transmitted power may not correspond to alignment of the fiber cores.

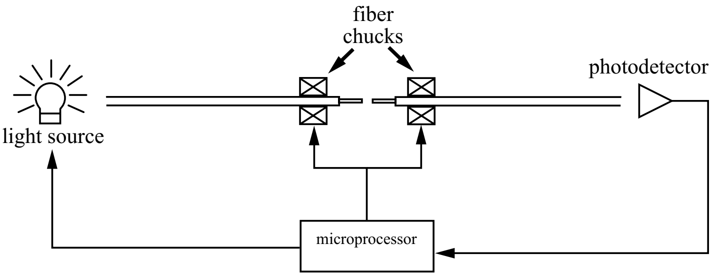

Fig. 2.13. Schematic illustration of a generalized transmitted-power based active alignment system. The arrows denote the flow of control to or from the microprocessor

Monitoring the transmitted power can also be used to determine when joint formation is completed, or when dopant diffusion has minimized the splice loss [2.37, 2.38] (dopant diffusion is discussed in Sect. 3.3). However, if the optical source used for alignment is relatively weak or if the power meter is a broadband detector, the inherent blackbody infrared emission of the heated fiber tips can affect the transmission loss measurement. Active alignment is most often used when fusion splicing erbium-doped amplifier fiber (EDF), although it is important to note that EDF strongly absorbs optical signals in its amplification band near 1550 nm so that active alignment of EDF is often performed at a wavelength of 1310 nm.

Another important disadvantage of active alignment are alignment errors associated with interference fringes that result from multiple reflections between the closely spaced end faces of the fiber tips. The refractive index difference between glass and air induces approximately 4% of reflection at a single fiber end face, which corresponds to about 0.3 dB of transmission loss. When the air gap is sufficiently small (less than about 20 microns), most optical sources, including light-emitting diodes (LEDs) and laser diodes (LDs), will exhibit a wavelength dependent loss associated with this reflection that varies between 0 and 0.6 dB [2.40]. The wider the bandwidth of the optical source, the smaller the air gap separation required for interference fringes, but only white light sources have a sufficiently broad spectral content to avoid these fringes during final fiber alignment when the separation between the fiber tips is on the order of 20 microns or less. Figure 2.14 shows how these interference fringes vary with the air gap distance between two conventional single-mode fiber (SMF) tips at 1550 nm. The figure shows that even perfectly aligned conventional SMF fiber tips with perfectly perpendicular cleave angles can exhibit nearly 0.6 dB of loss prior to fusion splicing. Minute variations in the fiber tip separation can occur during lateral alignment of the fiber tips. Since variations as small as 100 nm can induce several tenths of a dB variation in transmission loss, these interference fringes can confuse an active alignment algorithm.

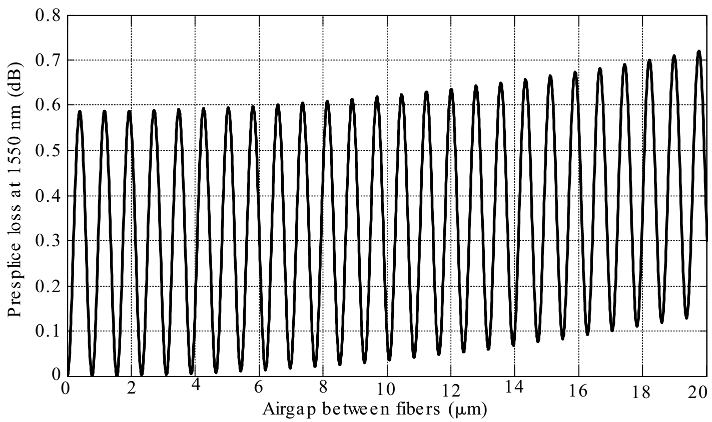

Fig. 2.14. Transmission loss across the air gap between two conventional single-mode fiber tips at 1550 nm. The sinusoidal fringes are caused by multiple reflections between the end faces of the fiber tips. The gradual loss increase at larger gap distances is caused by diffraction of the optical signal as it traverses across the air gap

2.3.4 Light-Injection and Detection (LID) Technology

Light-injection and detection (LID) is a transmitted-power based alignment system that does not require access to the free ends of the fibers to be spliced. Instead, an unstripped portion of the fiber near one of the tips is bent through a tight radius and illuminated with laser radiation [2.41–2.43] (Fig. 2.15). Bending an optical fiber, especially a single-mode fiber, induces loss because some of the light is scattered out of the fiber. Since a bent fiber can couple light out of the core into the external environment, light can also be coupled from the external environment into the core of the fiber. Brightly illuminating a fiber with a bend diameter on the order of several millimeters can couple a substantial amount of light into the core [2.42].

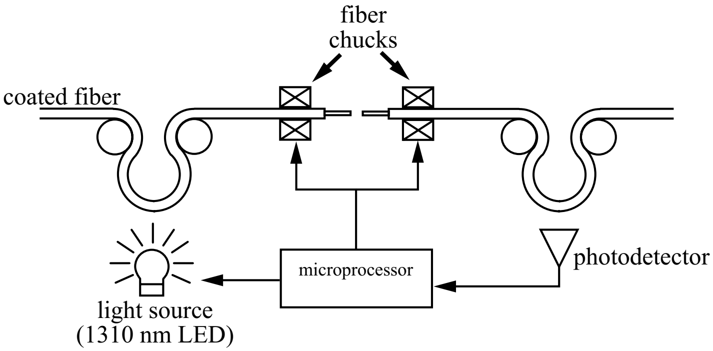

Fig. 2.15. Schematic illustration of an LID fiber alignment system. The coated fiber is bent near the fiber tips to launch light and detect light. The arrows denote the flow of control to or from the microprocessor

In order to detect the amount of light traversing the air gap between the fiber tips, a downstream tight fiber bend is situated near a photodetector. The tightly bent portion of the fiber must be coated to protect against breakage. Like other types of transmitted-power based alignment, LID is sensitive to the cleave angle. In principle, the LID system can also be used for loss measurement of a completed splice.

2.4 Summary

Optical fiber fusion splicing requires the initial fiber tips to be stripped and cleaved. These preparatory steps are important to the resulting splice loss, tensile strength, and long term mechanical reliability.

Stripping is necessary since the polymer coating cannot withstand the high temperatures of joint formation, and in many cases stripping permits superior fiber alignment since the glass geometry is much more precise than the polymer coating. Stripping can be accomplished with mechanical, thermo-mechanical, chemical, or vaporization techniques. Mechanical and thermo-mechanical techniques are well suited to all types of fusion splicing, but typically induce surface defects that reduce the tensile strength and long term mechanical reliability of the resulting fusion splice. Chemical and vaporization techniques permit much higher tensile strengths and superior mechanical reliability, but are more hazardous and more costly so they are restricted to laboratory or factory splicing. Chemical and vaporization stripping techniques are essential to high-strength fusion splicing.

Cleaving is a controlled fracture of an optical fiber intended to achieve a mirror-smooth, perfectly perpendicular fiber end face. Even the best cleaving instrument will periodically produce cleaves with defects. Cleave imperfections are a major source for splice loss variation between different splices fabricated with the same splicing parameters. Image processing built into most commercial fusion splicing equipment can detect cleave defects, especially end face angles. High quality cleaves are essential to low-loss fusion splicing of difficult-to-splice specialty fibers such as erbium-doped fiber (EDF) or dispersion-compensating fiber (DCF).

Prior to joint formation, the optical fiber tips must be aligned relative to each other. Some fusion splicing hardware employs passive alignment using fixed position v-grooves. More sophisticated alignment strategies include image-based active alignment in which the microscope images of the fiber's core or cladding are used for alignment purposes. Fibers can also be actively aligned based on the amount of optical power transmitted across the air gap between the fibers. Light-injection and detection (LID) permits active alignment based on transmitted power without requiring access to the fiber ends. Polarization-maintaining (PM) optical fiber fusion splices usually require that the fiber tips be rotationally aligned relative to each other.