Optical Fiber Tips and Their Applications

Joe Zhou, John Shannon, and James Clarkin

Introduction

What is an optical fiber end tip or simply a fiber tip? By definition, it is an optical micro-component sculpted on the end of an optical fiber which is used to reconfigure light entering or exiting optical fiber. One example is a fiber with a lens on the end. This performs nearly the same optical function as the combination of flat end fiber and a discrete lens on the optical path of the fiber axis.

Interest in fiber tips is rising with an increasing number of successful medical and industrial applications. Fiber tips bring high reliability/performance to the optical system because they are compact in comparison with the combination of optical fiber and discrete optical components and they reduce the number of optical interfaces thereby improving overall optical efficiency. Further, they are robust and require no alignment between the fiber and tip element. Environmental changes such as mechanical vibration and temperature variation do not degrade the performance. With discrete optics, optical alignment, which could be labor intensive and troublesome, must be performed before final system integration. Optical adjustment or re-alignment may be required on a regular basis in order to keep the system within the design specifications. In addition, fiber tips often cost less than a combination of fiber and discrete optical components, as the latter uses bulky, expensive or otherwise troublesome optical and mechanical components.

Sculpted fiber tips are not an addition of discrete optic components, but actual changes made to the optical fiber material itself. No additional glass material is needed in the process. For example, instead of bonding a lens to the fiber end a tiny lens can be sculpted on the fiber end as an integral part of the fiber, which results in a highly reliable fiber tip. Although the fiber tip modification may increase the cost of an optical fiber probe assembly, it may decrease the overall system cost because of fewer system components or smaller size. Reduced quantity of interfaces may enhance the system reliability/performance. It may be an enabling technology for applications where larger optical components are not feasible due to environmental restrictions. Fiber tips potentially have a high performance/cost ratio.

Sculpted fiber tips are useful in real-world medical and industrial applications such as:

- Materials processing which requires high power delivery,
- Laser ablation of body tissue and photodynamic therapy, which need even distribution of light over a relatively large area,
- High efficiency light coupling in communication links and material processing (welding and cutting), and
- Tissue ablation and perforation inside the human body, which sometimes redirects light away from the fiber axis in a limited space.

Typically, silica core/silica clad fiber is used to fabricate the tip. Occasionally, silica core and polymer clad fiber is employed. The fiber usually has a core diameter from 200μm to 800μm. The process can be either mechanical or thermal, often involving laser machining. Because the tip is a continuous, integral
part of the fiber itself, the interface between the shape and fiber is eliminated. Thus, there are no coupling losses and no potential for surface contamination encountered if the shapes were bonded to the fiber. This reduces optical loss and dramatically increases mechanical strength and durability of the device. When compared to a combination fiber and discrete optical lens, a fiber tip lens will have approximately 8% improvement in optical efficiency due to the reduction in Fresnel losses due to the elimination of two interfaces.

The most common fiber tips are tapers, lenses, diffusers, side-fire and angled ends. Examples of sculpted tips are shown in Table 1 and are discussed below.

**Tapers:**
A taper is formed by linearly increasing or decreasing the fiber diameter at one end. Ends where the diameter is increased are known as “Up” tapers (see Table 1). Ends with decreased diameters are known as “Down” tapers. These tapers can be used on either the input (proximal) end or on the output (distal) end.

“Up” tapers on the proximal end are typically used to increase the target surface area for high power applications, dramatically lowering the power density and improving the damage threshold of the fiber assembly. The light entering the taper encounters an increasing incident angle of light at the core clad interface along the length of the taper. Since high angle light will exceed the critical acceptance angle of the fiber the taper will effectively reduce the acceptance angle of light which will propagate down the fiber. Any incident light that exceeds this reduced acceptance angle will be stripped in the taper. These tapers are also used to convert a lower NA light source with a large spot size (high power laser beam) to a higher NA light source with a smaller spot size. It is worth noting that the portion of light stripped away is dissipated along the length of the taper. These tapers are useful in material processing such as welding and cutting, as well as in medical applications where a small flexible fiber is needed at the distal end.

An “Up” taper on the distal end is the same as an “Up” taper on the proximal end but light travels in the opposite direction. In this case, the output NA is reduced and the output spot size is enlarged. However, this configuration is not commonly used.

Used on the distal end, “Down” taper increases the output light NA and decreases the spot size. This taper is also called a cone tip when the taper is relatively steep. A cone tip is often used on the distal end in medical and dental applications where it increases light divergence over a small target area.

**Lenses:**

![Figure 1. Ball Lens Fiber Tip](image)
Various lenses such as concave, convex and spherical (ball) can be fabricated as a lens tip. These lenses are useful for modifying beam divergence and spot size. The shaped lenses are used to improve coupling from laser diodes to optical fiber, reduce Fresnel loss, change depth of focus, vary output spot size, and adjust light collimation. See Figure 1 for an example of a ball lens tip.

A convex lens has positive focusing power. An integral convex lens tip is often used to condense the light out the distal end. Conversely, a concave lens defocuses the light, spreading light over a larger area on the distal end. It is important to note the lenses described here are not typically good for collimating because relatively large spherical aberration leads to a diffused focal point. However, the ball lens fiber tip is often used to increase light coupling from laser diodes to fiber or improve light collection in sensors.

**Diffusers:**

![Diffuser Fiber Tip](image)

Figure 2. Diffuser Fiber Tip

Diffusers are generally used on the distal end to redirect and scatter the optical power evenly around the length of the fiber tip, like a lamp. The diffuser is typically fabricated with helical grooves or threads machined into the fiber clad material deep enough to extract and scatter light propagating down the fiber. The scattered light bathes an area with optical power, making it useful for applications such as photodynamic therapy or tissue ablation in urology procedures.

Because of relatively high scattering loss from deep grooves, diffusers are generally limited to distal end use and often enclosed in a glass cap for mechanical protection and for protection from contamination. Design of diffusers is usually not straightforward and requires substantial amount of experience. A trial and error approach is common although commercially available ray tracing software can be used for guidance. A decrease in optical power as light travels along the groove must be taken into consideration during design to obtain an even light scatter along the fiber tip. See Figure 2 for an example of a diffuser tip.
Side-Fire and Angled End:

![Side-Fire Fiber Tip](image)

A side-fire or angled end tip functions to redirect light to a relatively large area away from the fiber axis. Used on the distal end, the side-fire has found applications such as tissue cutting, ablation and perforation in urology, along with other medical procedures. In most side-fire designs, light in the fiber travels down the fiber to an angled end face and is reflected to the side approximately 90 degrees from the fiber axis. The optimal angle of the end face is 38 to 42 degrees. If 45 degrees were used, a significant portion of light will not be redirected to the side but will be lost by traveling axially as the critical angle is exceeded. Same as diffusers, the side-fire tip is typically enclosed in a glass cap to improve its mechanical strength and durability and to prevent contamination.

Angled end tips are generally used to reduce back reflection in the fiber. Machining a 7 to 10 degree angle on the fiber end will redirect the Fresnel back reflection at an angle outside the fiber acceptance cone defined by fiber NA and thus no back reflection will travel down the fiber. This is useful in high power medical and industrial application as back reflection could over-heat, burn and self-destruct the distal end or the section of fiber where there is a sharp bend. Similarly, used on the proximal end, the angled tip can dramatically reduce back reflection which may cause instability or damage in the laser source. In either case, heat sinking must be used to effectively dissipate the optical energy of the light that is reflected to the side.

It is interesting to mention recent successful applications of fiber tips and other fiber structures for spectroscopy. One application is a robust fluidic spectroscopic system based on a ball lens tip collecting fluorescence light over a windowed section of capillary tubing where the coating is removed for optical transmission from or to a fluid within the capillary. Another development is light guiding capillary tubing. The evanescent light travels longitudinally along the interface between the inner wall of the capillary and the fluid inside the capillary. The length of optical interaction with the fluid can be as long as the capillary itself, enabling sensitive detection of chemicals.

**Summary**
Sculpted optical fiber tips are versatile and useful for changing light spot size and divergence, improving optical efficiency, and redirecting light without the addition of discrete optical components within the system’s optical path. Fiber tips are compact, robust and highly reliable. Fiber tips can be cost efficient solutions for a variety of medical and industrial applications. Some features and benefits of typical fiber tips are summarized in Table 1.
<table>
<thead>
<tr>
<th>Fiber Tip Types</th>
<th>Schematics</th>
<th>Typical Tip Location*</th>
<th>Main Function</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Up&quot; Taper</td>
<td></td>
<td>Proximal</td>
<td>Increase spot size to decrease power density at surface for coupling high</td>
<td>Materials processing, tissue cutting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>power into fiber</td>
<td></td>
</tr>
<tr>
<td>&quot;Down&quot; Taper</td>
<td></td>
<td>Distal</td>
<td>Decrease spot size and increase divergence</td>
<td>Tissue ablation</td>
</tr>
<tr>
<td>Lens (Convex)</td>
<td></td>
<td>Proximal or Distal</td>
<td>Increase light collection / Decrease light divergence</td>
<td>Coupling</td>
</tr>
<tr>
<td>Lens (Concave)</td>
<td></td>
<td>Proximal or Distal</td>
<td>Increase light divergence</td>
<td>Spread illumination</td>
</tr>
<tr>
<td>Lens (Spherical Ball)</td>
<td></td>
<td>Proximal</td>
<td>Increase light collection angle</td>
<td>Sensors, diode laser coupling</td>
</tr>
<tr>
<td>Diffuser</td>
<td></td>
<td>Distal</td>
<td>Illuminate 360° through side of the fiber tip</td>
<td>Photodynamic therapy</td>
</tr>
<tr>
<td>Side-Fire</td>
<td></td>
<td>Distal</td>
<td>Redirect light sideways</td>
<td>Tissue ablation and perforation (e.g. Urological procedures)</td>
</tr>
<tr>
<td>Angled End</td>
<td></td>
<td>Proximal</td>
<td>Reduce back reflection</td>
<td>Communications, sensors, material processing</td>
</tr>
</tbody>
</table>

*Proximal end or input end; Distal end or output end.

Table 1. Sculpted fiber tip examples

For more information please contact Polymicro Technologies, a Subsidiary of Molex at polymicrosales@molex.com or by phone at (602) 375-4100.