# Design and Application of Bend-Insensitive Fibers

**Abstract:** In application, optical fibers are often bent into different shapes due to changes in their installation or use conditions. However, the performance and use of optical fiber will be seriously affected by the small bending radius. Therefore, not only should attention be paid to installation and use, but the optical fiber structure should be optimized by researchers to design a kind of bend-insensitive fiber. This article, with the loss of optical fiber, mainly describes the current popular structure design of bend-insensitive fiber and the influence of bending on the mechanical strength of fiber and introduces some application examples of bend-insensitive fiber.

**Keywords:** Bend-Insensitive Fiber; Macrobending Loss; Structure Design; Mechanical Strength; Bending Sensing;

## 1. Bending in optical fibers application

As an important signal transmission medium, optical fiber's biggest advantage is its flexibility but are optical fiber really "flexible"?

If the optical fiber is thin enough, it is "flexible" and "bendable" as long as it isn't broken. However, a small bending radius may lead to the loss of transmitted signals. In terms of its performance, the optical fiber should not be bent to a small radius. Thus, the installation of optical fibers and cables requires experienced engineers to carefully operate to avoid bending with a too-small radius. As shown in Figure 1, when the optical fiber is installed and fixed, it seems to be intact outside, but it has been bent.

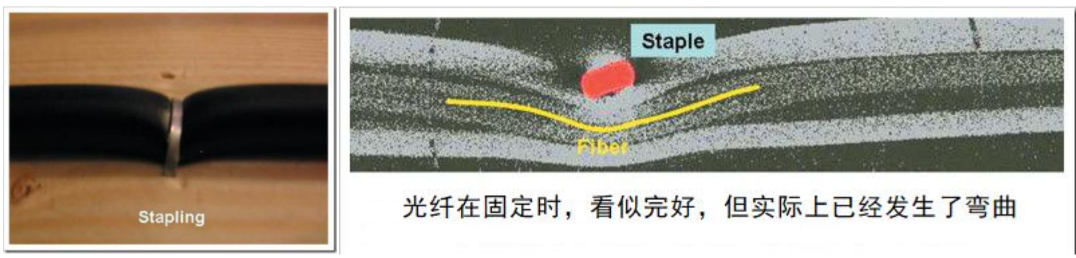


Figure 1 Bending example of optical fibers installation

## 2. Macrobending loss of optical fibers

Bending impacts on fiber performance are mainly reflected in bending loss.

The two parts of optical fibers bending loss are respectively macrobending loss and microbending loss[1]. Macrobending loss is caused in optical fibers laying, optical cable connection and other occasions. Microbending loss is caused in the process of optical fiber coating and fiber cabling, or by the change of ambient temperature and pressure. Generally, the optical power loss caused by fiber bending is mainly macrobending loss.

Macrobending loss of optical fiber is the loss caused by bending along the fiber axis. The beam is propagated by total reflection in the optical fiber; When the light beam is projected on the bending part, the propagation angle between the fiber core and the cladding boundary cannot meet the total reflection condition leading part of the light beam to escape from the fiber core and generate evanescent light, as shown in Figure 2. Therefore, because optical fiber is bent, the optical power of the outgoing light is smaller than that of the incident light, resulting in optical power loss, which is the main reason for the loss of light propagation in the bent optical fiber.

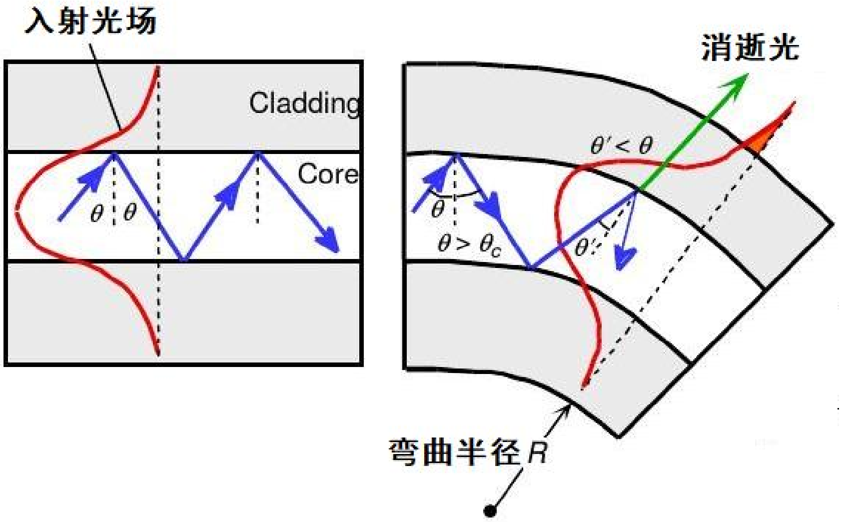


Figure 2 Diagram of macrobending loss of optical fiber

Bending an optical fiber seriously affects the optical propagation characteristics of the optical fiber. To avoid this situation, precautionary measures must be taken by installation personnel when bending optical fibers. **The rule of thumb for the minimum bending radius of optical fibers is: for long-term applications, the bending radius should be more than 150 times the diameter of fiber cladding; more than 100 times the diameter of cladding for short-term applications.** The cladding diameter of silicon dioxide fiber is usually 125um, so these two values are 19mm and 13mm respectively.

The loss $L$ caused by fiber bending can be expressed mathematically by the equation:

$$L = 10\lg\frac{\alpha}{\alpha + 2} + 20\lg\frac{NA'}{NA} \qquad (1)$$

Where, $\alpha$ is the refractive index distribution function, $\alpha=k(a/\Delta)^2$, where $\Delta$ is the relative refractive index difference, $\Delta=(n_1-n_2)/n_1$, $n_1$ and $n_2$ are the refractive index of fiber core and cladding respectively; And $a$ is the core radius; $k$ is a proportionality constant, which is related to material properties and bending radius $R$. $NA'$ is the numerical aperture of the optical fiber in the bending, NA is the numerical aperture of the optical fiber in the straightness, and the relationship between them is as follows:

$$NA' = [NA^2 - n_2^2(2 + a/R)a/R]^{1/2} \qquad (2)$$

$$NA^2 = n_1^2 - n_2^2 \qquad (3)$$

In addition, the bending loss of step index fiber can also be described by a dimensionless parameter MAC:

$$MAC = MFD/\lambda_c \qquad (4)$$

Where MFD is the diameter of the mode field, $\lambda_C$ is the cutoff wavelength. The bending loss is larger with the increase of MAC value.

According to the above formula, to reduce the bending loss of the optical fiber and improve the bending resistance, it can be realized by increasing $\Delta$, reducing $MFD$, or increasing $\lambda_c$.

**3. Several structural designs for reducing optical fiber bending loss**

On the one hand, a careful operation is necessary for optical fibers to reduce bending losses. On the other hand, flexible design is another important method to improve the bending resistance of optical fibers to realize this goal.

Several important formulas affecting the bending resistance of optical fibers are given above. According to the formulas (1-4) and actual production design, there are three main technologies to improve the bending performance of optical fibers at present: 1. Reduce the fiber mode field diameter or cladding diameter; 2. Increase the refractive index differences ($\Delta$) mainly differences between the fiber core and the cladding; 3. Hole-assisted fiber and nano-assisted fiber. Their essences are still to increase the refractive index difference. Corresponding common types of bend-insensitive fiber are shown in figure 3 [2].

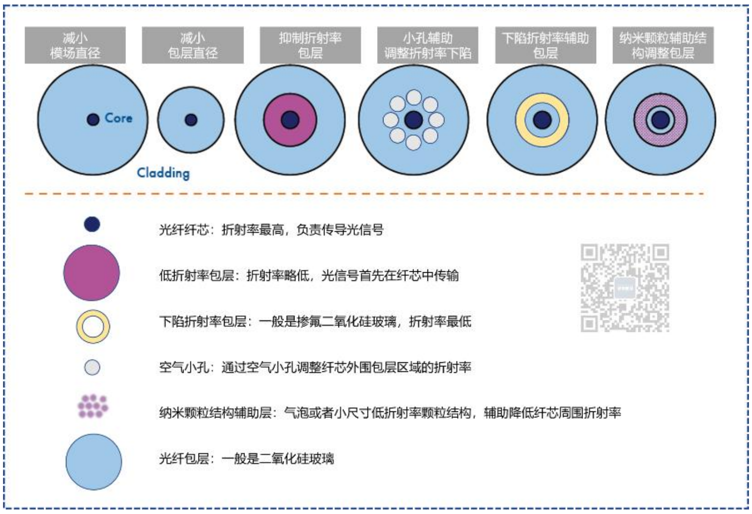


Figure 3 Diagram of structure design of several common bend-insensitive fibers

**Reduce the mode field diameter**: This is an intuitive design in which the refractive index of the core is increased with the reduction of the fiber core so that the beam can be better locked in the core.

**Reduce cladding diameter:** The fiber's bending resistance increases as its diameter gets smaller. Now the diameter of bend-insensitive fibers has been reduced from 125 um to 80 um, and even at 60 um.

**Suppression of refractive index cladding**: The refractive index difference between fiber core and cladding is increased.

**Trench-assisted refractive index cladding:** Adding a circle of low index grooves to the cladding is similar to increasing the refractive index of the core. The comparison of refractive index distribution of same standard single-mode fiber is shown in Figure 4.

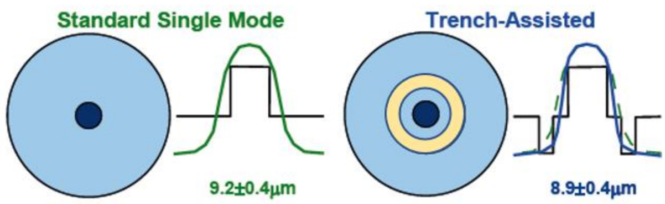


Figure 4 The comparison diagram of refractive index distribution between standard single-mode fiber and trench-assisted refractive index cladding

**Hole-assisted refractive index trench fiber**: Compared with bend-insensitive fibers whose refractive index distribution is changed by chemical-doping technology, the fiber has a completely different waveguide structure and symmetrical small holes around the core. Although hole-assisted fiber is not sensitive to bending, it is very expensive over long distances, relatively difficult to fuse, and incompatible with existing conventional standard devices.

**Nano-assisted bend-insensitive fibers:** This new optical fiber structure is advantageous in bending resistance and meets the requirements of optical fiber installation to the home, which is relatively easy to mass production and fusion compatibility. This design consists of a normal germanium-doping fiber core and a nano-engineered cladding, as shown in Figure 5.

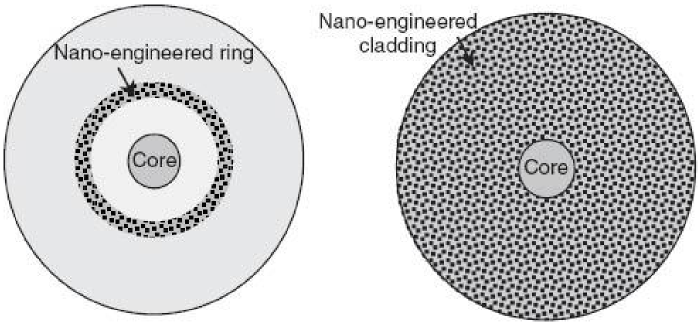


Figure 5 Diagram of bend-insensitive fibers with nano-engineered ring structure of different diameter in cladding

Among the six structures mentioned above, the first four are incremental optimization of the existing process, which has limited bending resistance. The hole-assisted optical fiber has the best bending resistance, but it is also the most difficult to manufacture and use. On this basis, the nano-assisted optical fiber is improved. Although loss part of the bending resistance, the mass production and use are greatly improved.

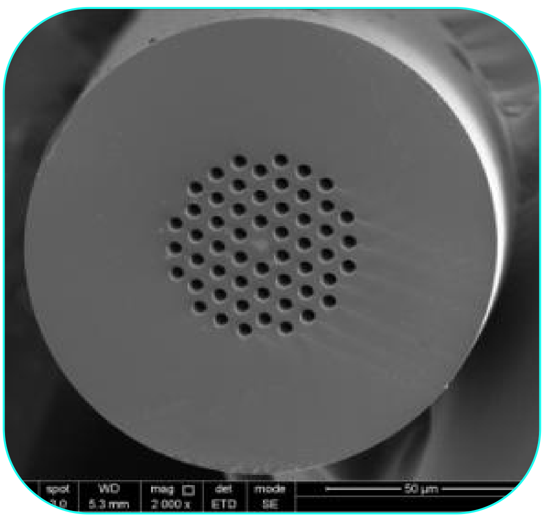

Figure 6 Diagram of total internal reflection PCF

In addition, as shown in figure 6, total internal reflection PCF has the same excellent bending resistance due to its cladding structure (periodic arrangement of cladding air holes) similar to that of hole-assisted fiber.

It should be noted that the above bending resistance is effective only when the optical fiber is not affected by external stress. If there is external stress at bending, its bending loss will be greatly increased, seriously affecting the performance and use of the optical fiber.

## 4. Influence of bending on the mechanical strength of optical fiber

Bending affects both **the optical properties** and **mechanical strength** of optical fibers. It can cause bending loss for optical properties, while in terms of mechanical strength, bending stress is generated at the bending point to increase the fracture probability of optical fiber and reduce the service life.

The mechanical strength of optical fibers is mainly determined by various defects (bubbles, impurities, internal or external defects, scratches, etc.) during manufacturing. Therefore, it requires improving the manufacturing process and materials to enhance the mechanical strength of optical fibers. Usually, only its tension available and mechanical strength meet certain requirements of the product, the products can be used by us. However, in the case of bending, the bending stress introduced by the bending strain outside and inside the fiber will inevitably affect its long-term mechanical reliability.

For example, Figure 7 is a reliability block diagram of fiber optic from Corning [3]. Where, the lower axis is the allowable bending radius (unit: mm) under the loading duration of three different bending stresses, and the upper axis is the corresponding allowable bending stress (unit: MPa, 7MPa is about 1kpsi). Assume that 1m optical fiber is wound on an optical fiber disk for storage and the radius of the optical fiber disk is 20mm. with sustaining bending, based on the time axis of “25 years”, the maximum bending stress on the optical fiber surface is about 275MPa or 40kpsi the probability of optical fiber fracture failure is less than $1\times10^{-6}$.

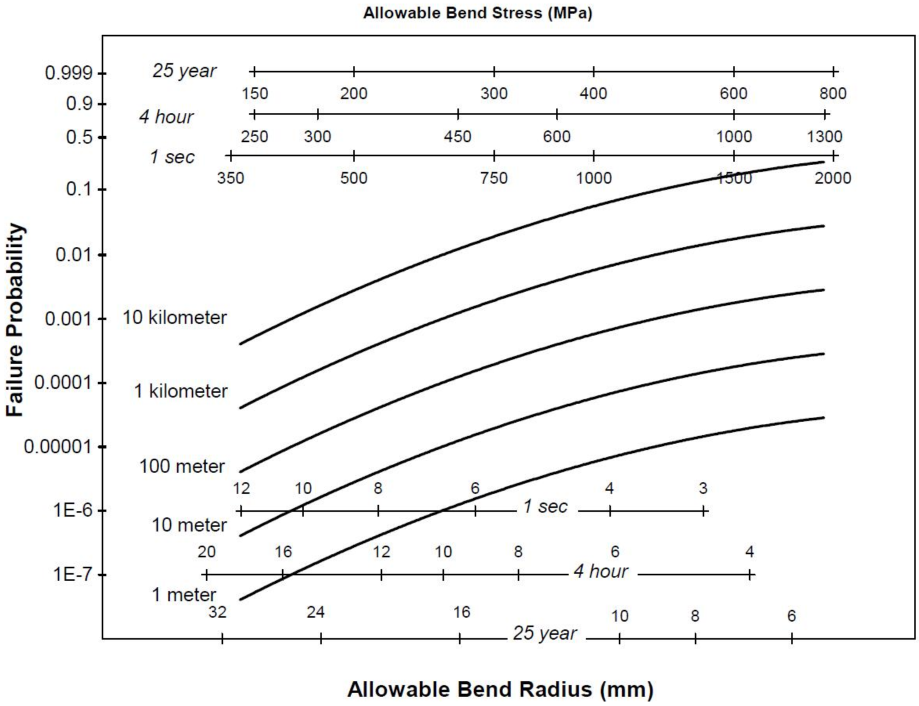


Figure 7 Outcome of optical fiber bending reliability test by Corning

Obviously, the smaller the bending radius, the larger the corresponding bending stress, and the higher the probability of fiber cut and failure.

## 5. Optical fiber bending sensor

In addition to communication applications, optical fibers are often used for sensing and detection. However, there are more stringent requirements for bending. Because optical fibers are often wound into various shapes. When bending to a certain extent, bending loss and refractive index changes caused by bending will cause serious interference to the results, which should be avoided as far as possible.

But it’s not all bad. Researchers have also developed radian, displacement, slip and pressure sensors by taking advantage of the bending properties of optical fibers.

Figure 8 is a typical fiber bending pressure sensor. the bending degree of sensing fiber and its output optical power is changed with different loading pressure *F*. Therefore, external pressure can be known by the change of optical power.

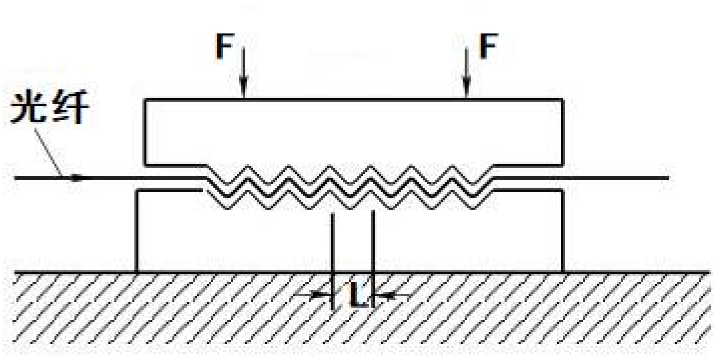


Figure 8 Typical pressure sensor structure of optical bending

A slippage sensor is produced by this principle, which plays a great role in the tactile sensing of the mechanical arm [4], as shown in Figure 9.

People can perceive whether the objects they grasp have the tendency of slipping without the aid of vision, and increase or decrease the grip strength accordingly as grasping objects with their hands. While a mechanical arm can’t do that, because the traditional manipulator does not have the function of slip detection, it must be installed with an external camera to judge the object slide and adjust the grasp. With a slippage sensor, the sliding friction between the object and the arm will deform the elastic body structure in the sensor to change the bending amplitude of the optical fiber. Finally, the grasping force can be adjusted by detecting the change of optical power.

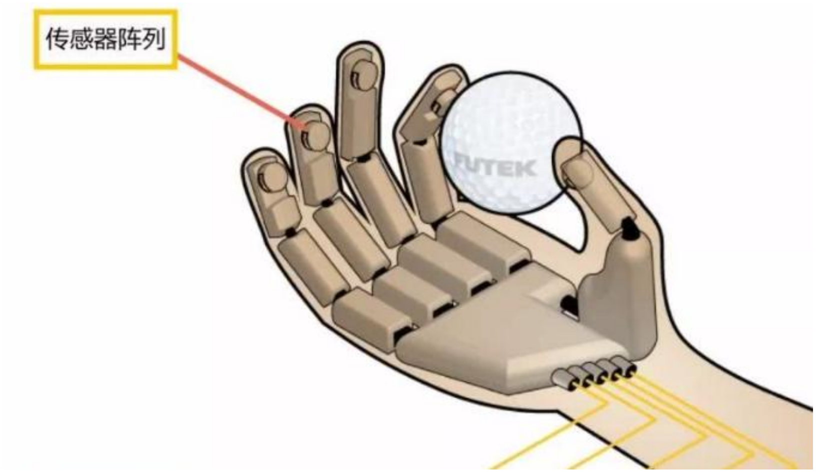


Figure 9 The application of slippage sensor in the mechanical arm

**6. Conclusion**

With the rapid development of broadband services, especially in the process of fiber-to-the-home, reducing the optical loss caused by bending and its influence on the mechanical strength of optical fibers is directly related to user experience. In addition, in some fiber optic sensing systems, interference caused by fiber bending is often required to be eliminated. Therefore, people not only set strict standards in the installation and configuration of optical fibers but also designed a variety of structure bend-insensitive fibers to meet the requirements of stricter bending conditions. However, other sensing systems in which the optical loss caused by bending or refractive index change is regarded as a monitoring object, how to improve the bending sensitivity of sensing fiber is the focus of researchers.

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