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Effects of the damage layer on connection loss of fiber-optic connectors

Xinlei Zhou*, Li Li, Bohan Lu, Ke Chen, Wei Peng, Qingxu Yu

School of Optoelectronic Engineering and Instrumentation Science, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

The damage layer, located at the endface of the fiber-optic connector, is currently the main intrinsic parameter that ultimately limits the connector's ability to achieve the lowest reflectance at the connection point. It deteriorates the connector's return loss and insertion loss and cannot be eliminated by mechanical method. We propose a method called chemical polishing, which is low cost and easy to operate, to eliminate the damage layer. Both theoretical and experimental work have been conducted to reveal the influence mechanism of the damage layer on the return loss and insertion loss. The results show that, by etching the damage layer in a low concentration (≤6%) hydrofluoric acid solution with a short etching time (≤40 s), we can effectively eliminate the damage layer and increase return loss without deteriorating the surface quality.

1. Introduction

Fiber-optic connectors are essential components in optical fiber transmission systems. To ensure good system performance, it is important to obtain high return loss from connection points as well as low insertion loss. There are several factors that can impact the return loss and insertion loss of fiber-optic connectors, such as end gap, lateral and angular misalignment, surface quality, damage layer and so on [1–5]. Today's connector design and production techniques have eliminated most of the challenges to achieve core alignment and physical contact. However, the damage layer, which is the result of polishing [6], has become the main intrinsic parameter that ultimately limits the connector's ability to achieve the lowest reflectance (*i.e.*, highest return loss). Although the return loss and insertion loss of today's fiber-optic connectors meet the requirements of the IEC standards, it still has a strong demand for higher-performance fiber-optic connectors in some specific fields, such as in military applications, aviation and aerospace applications and high speed communication systems [7–9].

The damage layer is an area on the connector's endface where the polishing process has compressed the glass giving a localized refractive index increase. Since the refractive index of the damage layer is slightly higher than that of the background fiber, it will affect the connection loss of fiber-optic connectors. Mechanical polishing process can ensure fiber-optic connectors own better endface surface quality and centering accuracy, but will inevitably produce a damage layer on the endface. How to reduce or even eliminate the damage layer to get better performance has become a tough problem in the production of fiber-optic connectors.

Several researchers [10–14] have studied the relationship between the damage layer (thickness and refractive index) and the polishing process (by varying polishing film types, pressures, times, etc.). These researches focus on improving the grinding and polishing process to reduce the impact of the damage layer on the return loss and insertion loss, but the damage layer cannot be eliminated as long as the polishing process exist. Li *et al* proposed an ultrasonic grinding method to eliminate the damage layer [15]. They obtain fiber-optic connectors with an insertion loss of less than 0.1 dB and a return loss of higher than 60 dB. However, the ultrasonic generator is complex, which make it has difficulties in actual use. In this paper, we present a chemical polishing method to eliminate the damage layer, which is low cost, easy to operate, and can increase the return loss of the fiber-optic connector.

2. Theory

The basic model of the connection is shown in Fig. 1, in which two optical fibers (refractive index of core: n_0) are connected. The end gap, and the lateral and angular misalignment between the fibers are not taken into account, as today's connector production technology can make sure the core alignment and physical contact. The two fiber endfaces have uniform damage layers (refractive index: n_1, layer thickness: h) as the polishing process are the same.

This model can be treated as a Fabry-Perot interferometer with a cavity length of $2h$ and a cavity refractive index of n_1. Based on the multiple beam reflection theory, the transmission coefficient and reflection coefficient of the fiber-optic connector can be expressed as [5]:

* Corresponding author at: No. 2, Linggong Road, Gangjingzi District, Dalian, Liaoning 116024, China.
E-mail address: xlzhou@dlut.edu.cn (X. Zhou).

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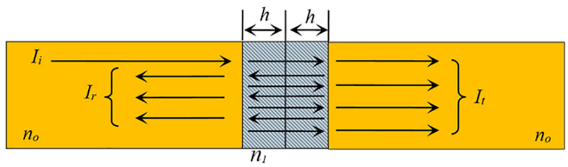

Fig. 1. Connecting model of fiber-optic connector with damage layer.

$$T = \frac{I_t}{I_i} = \frac{(1-R_0)^2}{(1-R_0)^2 + 4R_0\sin^2(4\pi n_1 h)/\lambda} \quad (1)$$

$$R = \frac{I_r}{I_i} = \frac{4R_0\sin^2(4\pi n_1 h)/\lambda}{(1-R_0)^2 + 4R_0\sin^2(4\pi n_1 h)/\lambda} \quad (2)$$

where I_i, I_t, and I_r are, respectively, the incident light, the transmitted light and the returned light, λ is the wavelength, and R_0 is the reflectivity at the refractive discontinuity between the core and the damage layer, which can be calculated by the Fresnel reflection equation:

$$R_0 = \left(\frac{n_0 - n_1}{n_0 + n_1}\right)^2 \quad (3)$$

Then the return loss (RL) and insertion loss (IL) of the connector are:

$$RL = -10\log R \quad (4)$$

$$IL = -10\log T \quad (5)$$

We can see from Eqs. (1)–(5) that the refractive index and layer thickness of the damage layer will have a directly effect on the return loss and insertion loss of the fiber-optic connector. Next, we will investigate the effects by numerical simulation and experiments.

3. Numerical simulation

In this section, based on the theory equation we present in Section 2, we use the Matlab to conduct the simulation, in which we take $n_0 = 1.463$, $\lambda = 1.550\,\mu m$. Fig. 2(a) shows the return loss varying with the refractive index and thickness of the damage layer. One can see that the return loss gradually decreases as the refractive index and thickness of the damage layer increase. Currently, the thickness of the damage layer is generally in the range of 30–40 nm and the refractive index is in the range of 1.48–1.53. In this range, the corresponding return loss is about 50 dB, which is consistent well with the actual fiber optic connector's return loss.

Fig. 2(b) shows the insertion loss varying with the refractive index and thickness of the damage layer. As the refractive index changes from 1.46 to 1.56 and the thickness changes from 0 to 50 nm, the insertion loss maintain in small values (in the 10^{-3} order of magnitude). Thus, we believe that the damage layer has little effect on the insertion loss.

The simulation results show that, in the actual fiber-optic connector manufacturing process, we should ensure the thickness of the damage layer as thin as possible while the refractive index of the damage layer as close as to that of the fiber core. In the ideal situation, we should eliminate the damage layer.

4. Experiments and discussion

We propose a chemical polishing method based on etching connector endface with hydrofluoric acid (HF) to eliminate the damage layer. Research have shown that HF can etch the silica fiber effectively [16–18]. For fiber-optic connectors, the optical fiber is mounted in a zirconia ferrule, leading to the etching behavior of the damage layer will be different with those bare optical fibers. Therefore, we need to investigate the etching behavior experimentally and expect to find appropriate etching parameters. Note that, the connector end's structure include three parameters: fiber height, radius of curvature and apex offset. As the radius of curvature and apex offset can be equivalent to the fiber height [5], the following experiments will only investigate the parameter of fiber height.

4.1. Etching rate

We dip connector's tip into different concentration HF solutions with different time. Then we measure the fiber height of the etched connector using the Norland Connect-Chek CC6000 automated non-contact interferometer system (purchased from Norland Products, Inc.), whose specifications and measurement procedure can be found in Ref [19]. As the damage layer located at the tip of the connector endface, the process of changing the fiber height is equivalent to the process of removing the damage layer. In experiments of this paper, for each measurement, we measure three connectors and take the mean value as our experimental data shown in following figures. Fig. 3(a) shows the change in fiber height (*i.e.* the damage layer thickness) varying with time in 2%, 4% and 6% HF solutions. We can see that the change in fiber height has a linear relationship with etching time. By linear fitting, we can get etching rates of 0.4 nm/s, 0.84 nm/s and 1.41 nm/s in 2%, 4% and 6% HF solutions, respectively. Furthermore, the change in fiber height after being etched 10 s in different concentration HF solutions are investigated, as shown in Fig. 3(b). One can see that when the HF concentration is lower than 18%, the fiber height change linearly with HF concentration, while has a significant increase as concentration larger than 18%.

4.2. Effects on return loss and insertion loss

The commercial return loss/insertion loss test station (FibbKey 7602, Lienhe Corp.) is used to measure the return loss and insertion loss of fiber-optic connectors after being etched. The return loss/insertion loss tester is a high performance loss test station that is designed specially for optical fiber testing, lab testing and passive components production. It integrates three different tests modes in one test station, working as a stable laser source, optical power meter and return loss

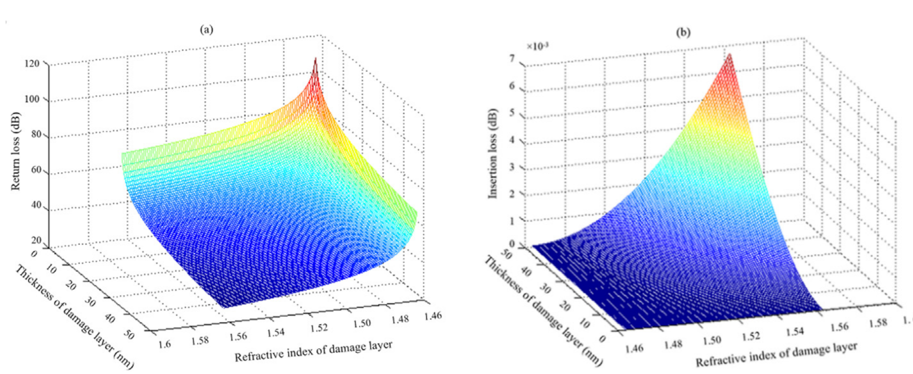

Fig. 2. (a) Return loss and (b) insertion loss vary with refractive index and thickness of damage layer.