Wavelength Insensitive, Non-contact and Highly Efficient Fiber Optic Connector using Up-tapered Multimode Optical Fibers

Tatsuya YOSHIHIRO*, Yukitaka ONO*, and Tadashi KASAMATSU*

Abstract

A wavelength insensitive, non-contact and highly efficient fiber optic connector has been created and demonstrated excellent performance. The fiber optic connector consists of a pair of up-tapered multimode optical fibers with an insertion loss of 0.9 dB in the range of 410 to 790 nm. With anti-reflective coating applied on the sections, the loss is expected to fall to 0.6 dB. We believe this novel fiber optic connector is suitable for multi-color illumination systems or devices subject to frequent connection and disconnection of the connector.

1. Introduction

1.1 Background

In recent years, with the increased trend for higher-functionality medical equipment, wavelength bandwidth of illumination used by a single piece of equipment has become broader, covering from the near-ultraviolet to near-infrared regions. Such cases include combined optical coherence tomography (OCT, 1300 nm) and laser induced fluorescence (LIF, 325 nm) endoscopy[1] and the simultaneous irradiation of diagnostic laser light (410 nm) and therapeutic laser light (630 nm) when combining photodynamic diagnosis (PDD) with photodynamic therapy (PDT)[2]. At the same time, optical communication between consumer appliances such as audio equipment and PCs has become common, using an extensive range of wavelengths from the visible to infrared regions.

A significant characteristic of those application examples is the simultaneous use of multiple-wavelength laser illuminations. In the future, the bandwidth used is expected to increase still further, which requires a high-efficiency optical connection between the light source and the scope, independent of wavelength.

In addition, when laser illumination is applied to the medical field as described, irradiation heads need to be detachable from light sources for sterilization. For use in consumer appliances, too, connectors require plugging and unplugging. In all cases, contactless optical connection is preferable to avoid damage to light sources and irradiation heads.

Aiming to achieve an unprecedented level of high performance to meet those demands, we designed and manufactured highly efficient, non-contact and wavelength-independent fiber optic connectors using up-tapered fibers[3) to 5)] of multimode fibers. As a result, we achieved an insertion loss of 0.9 dB (transmission efficiency of 81%) at wavelengths between 410 nm and 790 nm. Moreover, with anti-reflective coating on the end faces, we expect that an insertion loss will fall down to 0.6 dB (transmission efficiency of 87%). This paper describes the details of that newly developed connector.

1.2 Conventional optical connection methods

Fig. 1 shows a lighting system, consisting of laser light sources that output light to optical fibers while multiplexing several wavelengths, an irradiation head including optical fibers and an optical connection component for them, and Table 1 indicates general optical connection methods for that case.

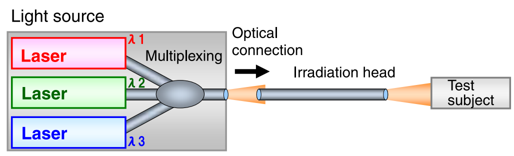
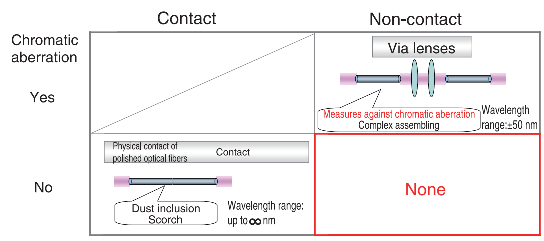


Fig. 1 Schematic diagram of multi-color laser illumination system.

Table 1 Fiber-optic connector types.



In optical communication, the most commonly used connection method is physical contact. Optical fibers, whose ends are shaped spherically via polishing for physical

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* Frontier Core-Technology Laboratories
Research & Development Management Headquarters
FUJIFILM Corporation
Ushijima, Kaisei-machi, Ashigarakami-gun, Kanagawa
258-8577, Japan

contact, are made to contact each other, by which high transmission efficiency with an insertion loss of 0.3 dB or less (transmission efficiency of at least 93%) is achieved over a broad wavelength bandwidth[6]. However, the connection is susceptible to dust on the fiber ends and not suitable for uses requiring frequent connection in environments that do not allow the cleaning of the ends.

On the other hand, there is a non-contact optical connection method involving lenses, mainly used in railway systems, ship-to-shore connection and military-use fiber optic connectors[6]. As the beam diameter becomes larger at the end of connectors, the connection is resistant against damage including scratches and achieves an insertion loss of 0.8 dB or less (transmission efficiency of at least 83%). However, there are some disadvantages in this method as follows: optical fibers must be aligned with lenses inside connectors; the diameter of fiber ends is not enlarged and this may cause optical pollution there; and lenses, which collect light by utilizing refraction, are susceptible to refractive index dispersion depending on the wavelength.

As a conclusion, there are no established methods for the connection of fiber optic connectors to meet the requirements of systems using laser light sources that have broad wavelength bandwidth.

2. Principle of the up-tapered fiber optic connector

This paper introduces the up-tapered fiber optic connector using up-tapered, multimode fibers, which is a wavelength-independent, non-contact connector with high transmission efficiency. This connector forms a non-contact joint, with a gap of 0.5 mm, by aligning two up-tapered fibers whose core diameter becomes larger toward their ends. Fig. 2 shows a model of the connector.

When geometrical optics is applicable, light transmitted inside a multimode fiber with a sufficiently large core diameter follows etendue conservation (law of conservation of radiance), as expressed by formula (1) below[7], provided the diameter of the core changes adiabatically.

$$r_{\mathrm{in}}\mathrm{NA}_{\mathrm{in}} = r_{\mathrm{out}}\mathrm{NA}_{\mathrm{out}} \qquad (1)$$

Variables r_{in}, $\mathrm{NA}_{\mathrm{in}}$, r_{out}, and $\mathrm{NA}_{\mathrm{out}}$ are, respectively, the core diameter of the light-incoming side, the numerical aperture of incoming light, the core diameter of the light-outgoing side and the numerical aperture of outgoing light. For example, if the core diameter of the light-outgoing side doubles while the etendue is conserved, the numerical aperture of outgoing light ($\approx$ beam divergence angle) halves. The up-tapered light connector uses this principle and reduces optical coupling loss derived from the distance between the end faces.

That change of the beam divergence angle happens because light transmitted inside the optical fiber is totally reflected in the tapered region by the angled side walls. Based on geometrical optics, the beam divergence angle decreases by the taper angle every reflection on the side walls of the tapered region. Therefore, different from optical elements such as lenses that depend on refraction, the decrease of the beam divergence angle of up-tapered fibers is almost independent of the wavelength, and this property enables high transmission efficiency over a broad wavelength range.

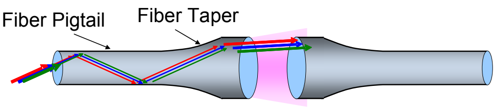

Fig. 2 Fiber optic connector using up-tapered optical fibers.

3. Design and manufacture

3.1 Design of the up-tapered fiber via geometrical optics simulation

Parameters that can be designed in the up-tapered fiber optic connector are the core diameter magnification and the taper length. To investigate optimal parameter values, with the geometrical optics simulation software ZEMAX (developed by Radiant Zemax), we calculated insertion loss for the former parameter while the latter was fixed, and obtained the former parameter value for which the insertion loss became minimum.

Fig. 3 shows the model of the up-tapered fiber optic connector used in this simulation. The core refractive index and clad refractive index of the optical fiber used (NA of 0.22) were 1.45 and 1.433 respectively. The core and clad diameters of the non-tapered region were 104 µm and 126 µm respectively. The up-tapered region approximated a 10-mm-long cone. We calculated insertion loss while enlarging the core/clad diameters respectively from 104 µm/126 µm up to two to six times those values. The simulation results are shown in Fig. 4. Note, however, that the influence of reflection at the fiber ends was ignored.

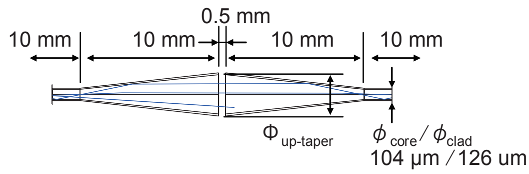

Fig. 3 Simulation model of up-tapered fiber-optic connector for ray trace.

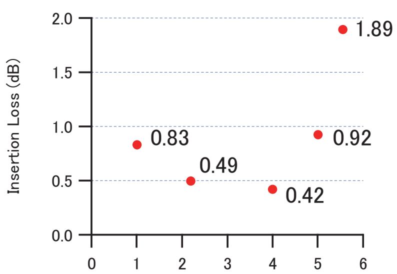

Fig. 4 Calculated insertion loss of up-tapered fiber-optic connector.

The results indicate that insertion loss became the smallest, 0.42 dB (transmission efficiency of 91%), when the core and clad diameters of the up-tapered fibers were quadrupled. For smaller magnification, insertion loss derived from the gap was considerable. On the other hand, for larger magnification, it is likely that insertion loss increased because the up-tapering angle was too steep for the fiber to be regarded as adiabatic and that prevented the ideal beam conversion.

3.2 Manufacture by heating, drawing and fusion splicing

Based on the results of the geometrical optics simulation, we manufactured, by way of a trial, a fiber tapering up from the core/clad diameters of 105 μm/125 μm to about four times those values, i.e. 400 μm/500 μm, respectively.

On the market, there already exist up-tapered fiber products whose taper length is on the order of a few meters. However, as those fibers are manufactured from preforms by changing the drawing speed, they produce much surplus in the process and are very expensive. In addition, their size reduction is not easy. To respond to that issue, we sought a new method to create a more compact product at a lower cost. Specifically, by heating and drawing, we first manufactured a down-tapered fiber[8] from a large-diameter quartz optical fiber, whose core diameter will become smaller toward the end, with core/clad diameters of 400 μm/500 μm and an NA of 0.22; then, by fusion splicing it to another non-tapered quartz optical fiber with core/clad diameters of 105 μm/125 μm and an NA of 0.22, we created an up-tapered fiber. The following are the manufacturing steps.

1. Remove the cladding from a large-diameter fiber
2. Taper down the fiber by heating and drawing
3. Cleave the down-tapered fiber
4. Fusion splice the down-tapered fiber to another non-tapered fiber to create an up-tapered fiber
5. Terminate the end of the up-tapered fiber with an FC connector
6. Apply optical polish to the fiber end

Fig. 5 shows the image of the up-tapered fiber patch cable.

Fig. 5 Up-tapered fiber optic patch cable.

4. Evaluation

4.1 Decrease of the beam divergence angle

A good-quality beam diameter conversion in the up-tapering region can decrease the divergence angle of the beam exiting from the fiber according to etendue conservation. As the magnification of the up-tapered fiber described in this paper is four, the beam divergence angle should become one-fourth that of a non-tapered fiber. The decrease of the beam divergence angle was confirmed by measuring the far-field patterns of the beam exiting from the up-tapered fiber. Fig. 6 is the cross-sectional profile of the measured far-field patterns.

By definition of the beam divergence angle as an angle that includes 63% of the total energy of the beam[9], the angle for the up-tapered fiber was 2.6° while that for the non-tapered fiber was 10.2°. The beam divergence angle was definitely reduced to one-fourth, which means a good-quality beam diameter conversion took place.

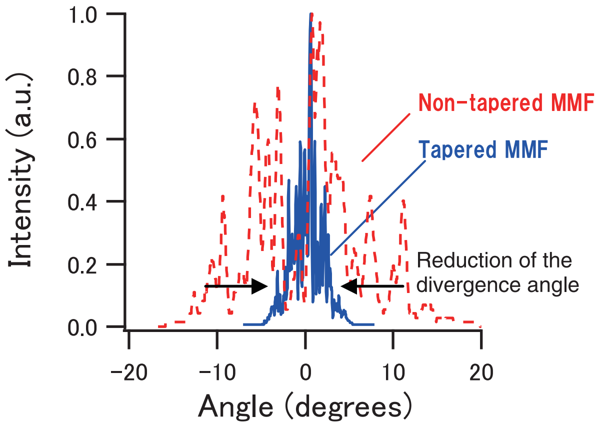

Fig. 6 Sections of far-field radiation patterns of the up-tapered multimode fiber (solid line) and non-tapered multimode fiber (dashed line).

4.2 Wavelength dependence of insertion loss

The insertion loss of the manufactured up-tapered fiber optic connector was measured at wavelengths of 410 nm, 450 nm and 790 nm. Fig. 7 shows the measured values when the distance between the fiber ends was 0.5 mm.

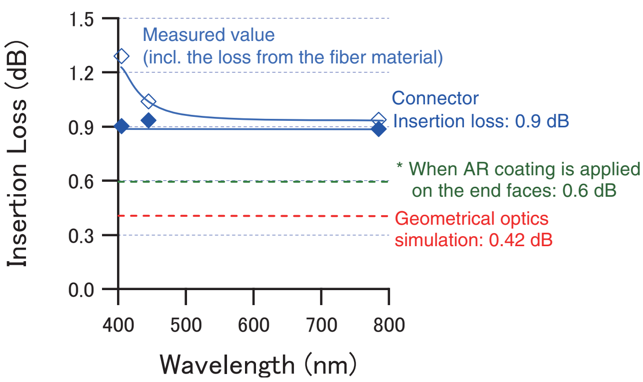

Fig. 7 Insertion loss of up-tapered fiber optic connector, the values measured and calculated by ray trace.

The results revealed that the measured insertion loss increased at a wavelength of 410 nm. The absorption and scattering characteristics of the fiber material are considered to have been the cause. After subtracting the loss from the material itself measured with a non-tapered fiber of the same length, the insertion loss of the connector, which is independent of the wavelength, is 0.9 dB (transmission efficiency of 81%)[10].

Anti-reflective coating was not applied to the ends of the trial optical connector. If the loss from the reflection at the end faces were reduced by applying the coating, the insertion loss could decrease to 0.6 dB (transmission efficiency of 87%). That value approaches the 0.42 dB (transmission efficiency of 91%) obtained in the geometrical optics simulation. We infer that the excess loss of 0.18 dB (4%) originated from the disturbance on the splice point and the tapering side walls.

5. Conclusion and prospects

With several sample up-tapered fiber optic connectors, we succeeded in achieving an insertion loss of 0.9 dB (transmission efficiency of 81%) at wavelengths of 410 nm, 450 nm and 790 nm. It also became apparent that, by applying anti-reflective coating, the insertion loss is expected to be reduced to 0.6 dB (transmission efficiency of 87%).

In spite of the non-contact type optical connection, the up-tapered fiber optic connector introduced in this paper can achieve high transmission efficiency over a broad wavelength bandwidth. Therefore, the connector is suitable for equipment that requires a broad range of wavelengths from illumination and the frequent plugging and unplugging of optical connections, for example, laser endoscopes with multi-colored excitation light sources and photo-sensing fiber devices. In addition, because of its large core diameter, the end face of the fiber optic connector can be more resistant to damage. In the future, we expect to introduce the connector into an extensive range of optical applied equipment such as optical interconnects[11] that requires users to plug and unplug connections on a daily basis.

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