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Optical Coupling Optimization for Fiber Lasers and Devices

Invited Paper

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ABSTRACT

We review fundamental waveguide optics at a fiber joint between dissimilar specialty fibers and its diffusion characteristics when the joint experiences thermal treatment. We then describe optical coupling techniques including thermal diffusion and fiber tapering in order to achieve minimum transmission loss through the fiber joint. We discuss the optical coupling property change due to diffusion and the effect of fiber taper ratio and taper length with application examples.

Keywords: Optical coupling, diffusion, fiber taper, specialty fiber, waveguide optics, fusion splicing, transmission optimization, fiber laser, fiber device

1. INTRODUCTION

Optical fibers are widely used in fiber lasers and devices for metal cutting, welding, material processing, remote sensing, and optical telecommunications. Efficient and high quality optical coupling between different fibers in these devices ensures the performance and long term reliability of fiber lasers and fiber systems. Emerging specialty fibers, such as large mode area fibers and microstructured fibers, pose a new challenge to optical coupling techniques between fibers because of their distinct fiber properties. New coupling techniques need to be developed and a more in-depth understanding of optical characteristics at the splice joints is required [1], [2], [3], [4]. Fusion-splicing [5], a method which heats fiber tips to a sufficient high temperature (approx. 2000°C for silica fibers) for fibers to be bonded together, has been widely used to interconnect optical fibers with low loss optical transmission between dissimilar fibers. When two fibers are fusion-spliced together, a longitudinally varying transition region at the splice joint is created. The transition of the optical waveguide property at the splice joint leads to optical field change when the light propagates through the splice. As a result, optical transmission loss occurs at the joint. Optimal coupling of dissimilar fibers therefore depends on the proper optimization of the thermal treatment around the joint.

In this paper, we first discuss fundamental theories that govern the optical transmission and thermal diffusion at the fiber joint between two dissimilar fibers when they are subjected to a thermal treatment. We then present some advanced techniques, including the thermally expanded core and the tapered fiber method, to achieve optimal fiber coupling. We will provide both analytical and experimental results.

2. FUNDAMENTAL WAVEGUIDE AND DIFFUSION OPTICS

When the tips of two fibers are treated with high temperature during fusion-splicing, the dopants (e.g. Ge, F, Al) in the fiber core of the treated fibers diffuse. As a result, the mode fields of two fibers are changed and transition tapers are created. A schematic of the fiber transition zone is shown in Fig. 1. Transmission loss occurs at both the taper region and the splice interface. Ideally, the taper needs to be adiabatic and the mode-fields of both fibers at the splice interface need to be perfectly matched.

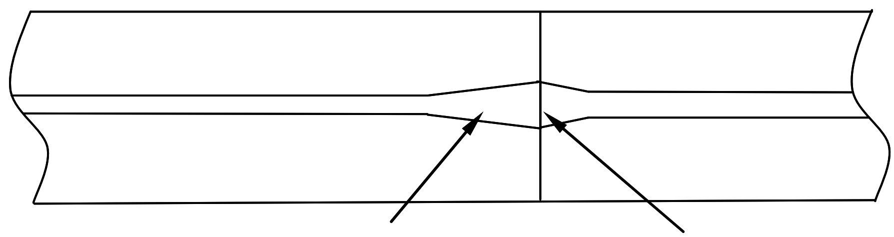


Fig. 1 Schematic of a splice joint formed by fusion-splicing of two dissimilar fibers

A full quantitative description of the field propagation from one fiber to the other through the splice transition region requires solving the Maxwell's equations with associated boundary conditions based on the actual waveguide properties of two dissimilar fibers and the optical characteristics of splice transition. For the light transmitted in a weakly guided fiber core, the electrical field components in the fiber are governed by the Helmholtz equation [6], which can be expressed as following assuming that the fiber is cylindrically symmetric.

$$\frac{\partial^2 \varphi}{\partial r^2} + \frac{1}{r}\frac{\partial \varphi}{\partial r} + \frac{\partial^2 \varphi}{\partial z^2} + n^2(r,z)k^2\varphi = 0 \qquad (1)$$

where φ is the electric field, n is the fiber refractive index, k is the wavenumber, r is the radial coordinate, and z is the longitudinal coordinate.

The interaction between different fields in the fiber transition taper can de described by the coupled mode theory. The evolution of the field is a superposition of many Eigen modes [7], [8]. Numerically, the Helmholtz equation and the coupled mode equation can be solved using the finite beam propagation method (BPM) with commercially available softwares, e.g. [9] based on the fiber property and boundary conditions.

When a fiber is subjected to a heat treatment, the dopant in the core diffuses and this leads to fiber waveguide property change [10]. The dopant diffusion can be analytically described by Fick's law [11], which is shown in Eq. (2) by again assuming cylindrical symmetry of the fiber.

$$\frac{\partial C}{\partial t} = D\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right)\right] \qquad (2)$$

where C is the local dopant concentration, r is the radius, t is the time, and D is the dopant diffusion coefficient, which can be described by the following Arrhenius equation for the silica glass.

$$D = D_0 \exp\left(-\frac{E}{RT}\right) \qquad (3)$$

where D_0 is a diffusion constant, E is the activation energy, R is the ideal gas constant, and T is the temperature. Eq. (2) needs to be solved numerically based on the initial dopant distribution. The diffusion equations can be used to analyze the dopant diffusion characteristics at the fiber joint and the transmission property of electric fields across the joint. This analytical approach can be used to optimize the core diffusion with *a prior* knowledge of the dopants.

To further understand the transmission loss, it is convenient to decompose the total loss at the joint into two parts, (1) the mode-field (MF) mismatch loss and (2) the transition taper loss. As shown schematically in Fig. 1, the taper loss occurs in the transition taper zone when the light propagates through the tapered area. Generally, both fibers experience the transition loss if the taper is not adiabatic. On the other hand, the mode-field mismatch loss occurs at the interface between two fibers because of the waveguide property difference at the vicinity of this interface. To a lesser degree, losses due to light scattering and reflection occur at the splice joint. It is also important to note that the transmission loss is wavelength dependent [12].

To determine the tapering loss, it is necessary to solve Eq. (1) and the coupled mode equation numerically. The mode-field mismatch loss can be estimated based on the overlap integral of the field amplitudes of the guided modes using the following equation,

$$Loss\ (dB) = -10\log_{10}\left[\iint \varphi_A(r,\theta)\cdot\varphi_B(r,\theta)\,dr\,d\theta)\right]^2 \quad , \tag{4}$$

where $\varphi_A(r,\theta)$ and $\varphi_B(r,\theta)$ are the normalized field amplitudes of the guided modes for two fibers A and B. For a step-index fiber, the guided modes can be solved exactly [12], [13] to determine the mode-field mismatch loss.

3. OPTICAL COUPLING OPTIMIZATION TECHNIQUES

For optimal coupling between dissimilar fibers, the transition taper needs to be ideally adiabatic and the mode-field of two fibers at the fiber interface needs to be matched perfectly. To achieve this goal, we describe two techniques, the thermally expanded core (TEC) method and the tapered fiber method.

The TEC method utilizes the thermal diffusion of the dopant in the fiber core to change the local waveguide property (index profile) of the fiber. The fiber core is generally doped with germanium (Ge) and/or aluminum (Al) to raise the refractive index and sometimes with fluorine (F) to reduce the index. When the fiber core is treated at a high temperature, the dopant in the core becomes mobile and is diffused into neighboring glass. The diffusion characteristics, which depend on the dopant, its distribution, and the fiber waveguide property, can be described by the Fick's law shown in Eq. (2). When the fiber core is doped with Ge or Al, the diffusion increases the fiber mode-field diameter (MFD). Therefore, it is possible to minimize the transmission loss at the splice interface by properly matching the mode-field property. In addition, it is desirable to have a sufficient diffusion taper length to minimize the tapering loss. One technique to create a long dopant diffusion taper length is to scan a splicer head back and forth across the fiber. As most heat is applied to the center of the fiber treatment area, the mode-field changes the most at this point. The taper length can be controlled by the scan length of the splicer head. A scan length of 1 mm is usually sufficient to create a lossless adiabatic taper for a typical fiber. Therefore, the transmission loss between two distinctly different fibers can be significantly reduced using this method.

To demonstrate this technique, we thermally diffuse a 1060 single-mode fiber with a 920-nm cutoff wavelength. We scanned the splicer head back and forth across the bare glass section for multiple times. Then we precisely cleaved the fiber at the middle of treatment area. The mode-field change was measured using a far-field scanner. The MFD of the original fiber is 6.5 µm at 1060 nm. With proper treatments, we are able to expand the MFD diameter up to 20 µm -- a three-time mode-field expansion. An example of far-field measurement results with different mode-field expansions is depicted in Fig. 2. A decrease of NA in far-field measurement corresponds to a increase of the fiber MFD. In this case, the MFD of the fiber is expanded to 11.5 µm and 17.5 µm from 6.5 µm, respectively.

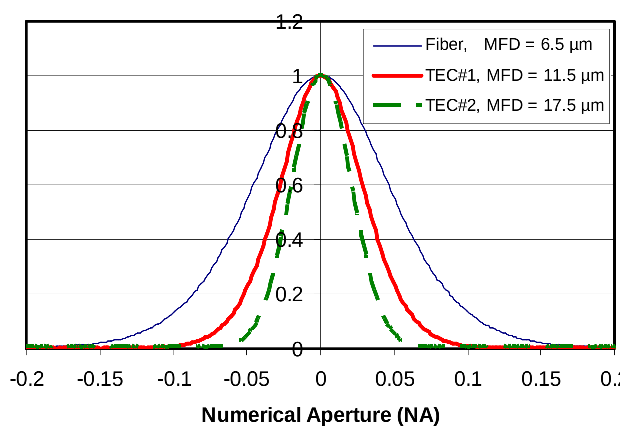


Fig. 2 Far-field measurement results with the TEC method

As an application example, we used the TEC method to minimize the transmission between a SM 1060 fiber and a LMA fiber. The MFDs of the 1060 and LMA fibers are respectively 6.5 µm and 12.4 µm at 1060 nm. This translates a theoretical mode-field mismatch loss of 0.73 dB without mode-field expansion. To optimize the optical coupling between these two fibers, we used a filament-based fiber splicing system, which can precisely control the fiber position and the splicer head. Compared to the electrode-based splicing, the filament-based splicing has a wider heat treatment zone, which leads to a longer tapering zone with lower transmission. In the TEC process, we first splice two fibers together with a precise core alignment. We then thermally expand the fiber core by scanning the splicer head. We actively monitored the transmission during this process. The transmission loss changes versus the time duration of the thermal treatment are shown in Fig. 3. The loss between these two fibers is reduced from the original 0.8 dB to 0.03 dB with about three-minute thermal diffusion. The transmission loss increases slightly with additional diffusion treatment. Two microscopic images of the fiber joint before and after the diffusion are shown in Fig. 4. The waveguide discontinuity is clearly seen in the pre-diffusion image, but not in the post-diffusion image. The estimated mode-field distributions before and after diffusion at the joint are shown in Fig. 4.

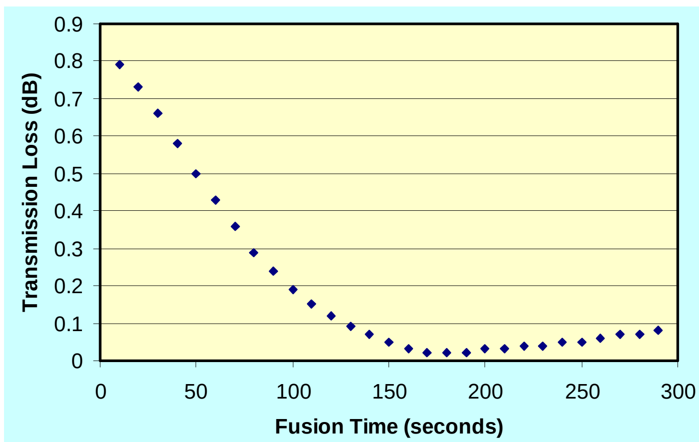
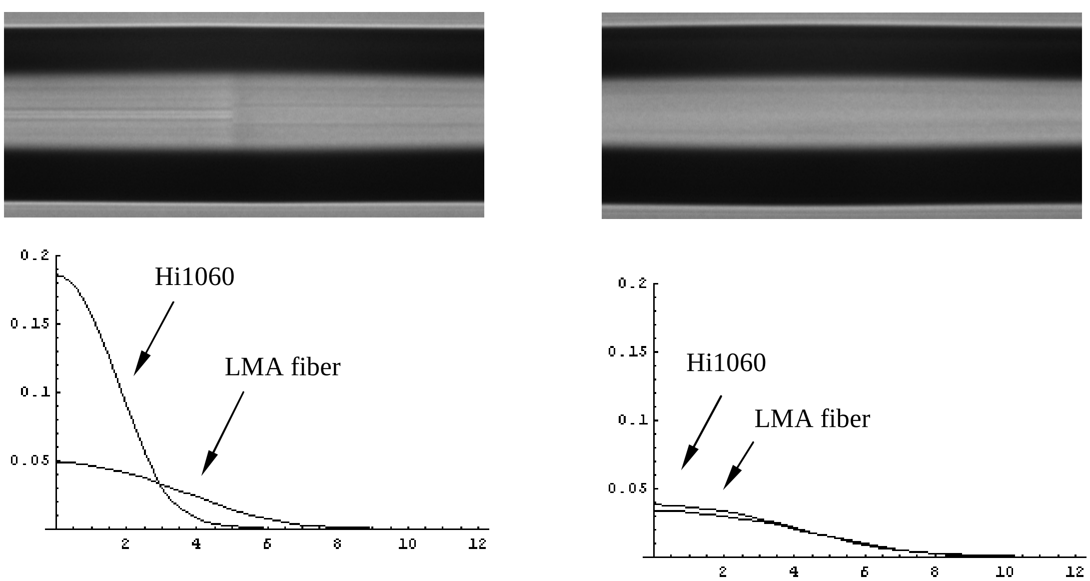


Fig. 3 Optical coupling optimization using the TEC method
(between a SM 1060 fiber -- MFD of 6.5µm and a LMA fiber -- MFD of 12.4µm)



(4.1) pre-diffusion (4.2) post-diffusion

Fig. 4 Microscopic images and mode-field profiles at the fiber joint before and after diffusion

Instead of changing the dopant distribution or the refractive index profile of the fiber, we can physically taper a fiber to change the size of the fiber core or the fiber V number, and thus the fiber modal property. An example of a tapered fiber image and the input and output mode-fields are shown in Fig. 5. For a fiber with a step index profile, the fiber's LP_{01} fundamental mode-field profile can be computed analytically by solving the Helmholtz equation (1). With a fixed index Δn, the mode-field varies with the fiber core size. The calculated MFDs for a fiber with different numerical apertures and core diameters are shown in Fig. 6. As we can see the MFD change has a saddle shape. For a given NA, the MFD decreases as the core size increases, reaches a minimum, and then increases again. Thus, it is possible to match the mode-field of two fibers via fiber tapering. While MFD provides a quantitative number to define the fiber modal size, we have to be cautious that MFD is a highly simplified parameter. If two fibers have the same MFD value, it does not necessarily mean that these two fibers have a perfect mode-field match. The overlap integral, equation (4), of mode-field profiles between two fibers provides a better indicator for the mode-field matching. An example of calculated loss between LMA fiber #1 – 0.06 NA and 20 μm core diameter and LMA fiber #2 – 0.08 NA and varied core diameter is shown in Fig. 7.

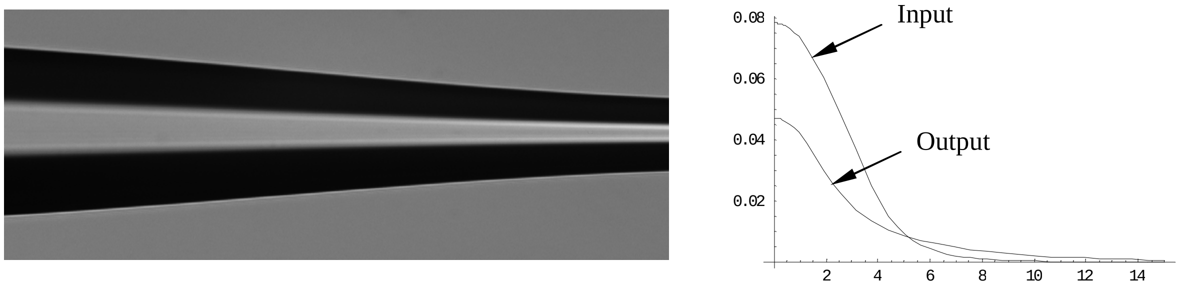


Fig. 5 A tapered fiber image and the mode-field change due to the tapering

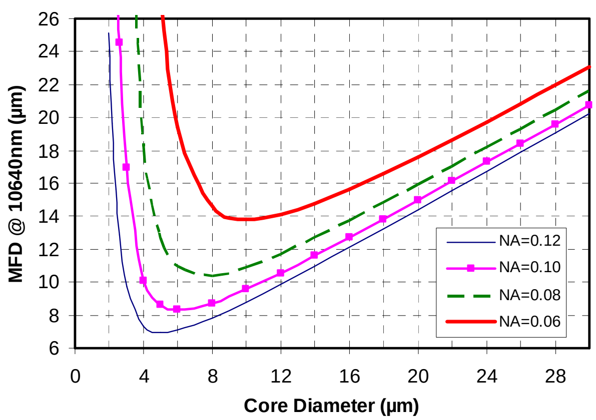


Fig. 6 MFD for fibers with different NAs and core diameters

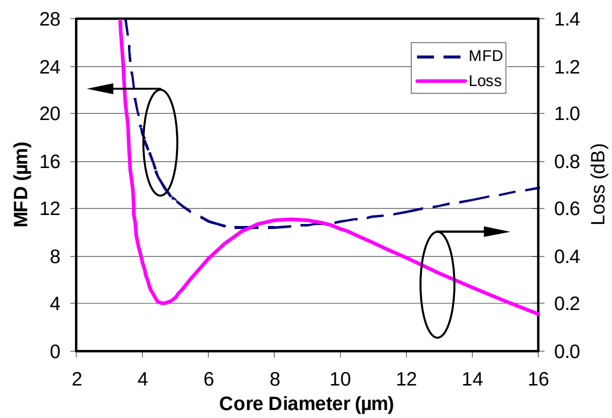


Fig. 7 Mode-field mismatch loss between fibers with 0.06NA/20μm and 0.08-NA with varied core diameter

To achieve optimal coupling using the tapered fiber method, we also need to properly control the taper length. A short taper length could lead to a transmission loss due to generation of leaky modes. A long taper length can eliminate the tapering loss with added fiber processing control requirement and complexity. So the tapering length needs to be optimized. We use the BPM method to estimate the transmission loss due to the fiber tapering. We use two different fibers as an example. Fiber #1 has a 20-μm core diameter and a 0.06 NA, and fiber #2 has a 10-μm core diameter and a 0.08 NA. The tapering ratios (TR) of two fibers are 3.0 and 2.0, respectively. The tapered fiber has a tapered section and a straight section. We vary the taper length in the calculation, and the length of the straight section is assumed to be 5 mm. The results of the calculated transmission loss for these two fibers shown in Fig. 8 indicate that the minimum taper length without incurring tapering loss is around 15 mm. With a short taper length of 4 mm, the transmission loss is about 10%. This result helps set up a guideline for determining the fiber taper length when we use the tapered fiber method for optical coupling between dissimilar fibers.

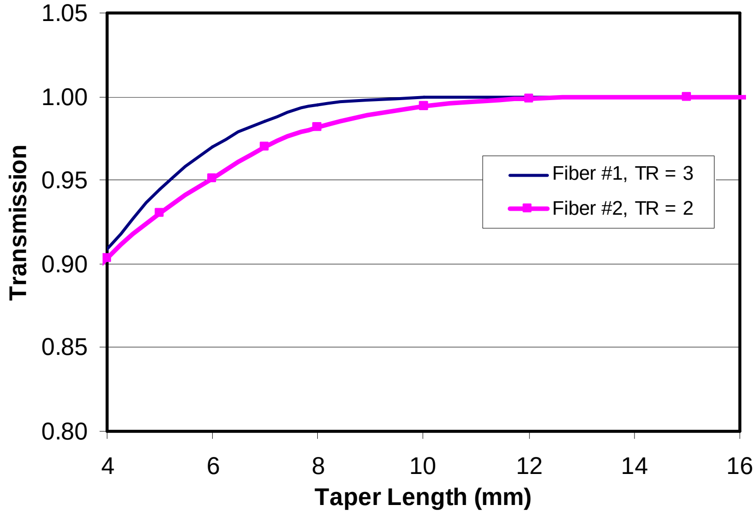


Fig. 8 Transmission loss for different fiber taper lengths
(fiber #1 – 0.06NA/20μm and fiber #2 – 0.08NA/10μm)

4. CONCLUSIONS

We described fundamental waveguide optics and diffusion at the fiber joint of dissimilar fibers. When the fiber joint is subjected to thermal treatment and the geometry changes, theoretical prediction of the resulting waveguide property of the joint requires solving the beam propagation equations and dopant diffusion equations. Informed by theory, empirical approaches can be used to optimize dissimilar fiber splices. The theoretical and experimental results presented show that thermally diffusing the fiber core and physically tapering the core are two useful techniques for achieving optimal optical coupling between dissimilar specialty fibers. Independent or concurrent use of these techniques provides a powerful tool for reducing the transmission loss between dissimilar fibers.

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