

Low-Loss High-Strength Microstructured Fiber Fusion Splices Using GRIN Fiber Lenses

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Abstract: Gradient-index fiber lenses are used to fabricate high-strength (>100 kpsi) fusion splices between microstructured optical fibers. High coupling efficiencies are attainable (<0.6 dB loss), providing the mode field diameter is at least about 3.5 μm .

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1. Introduction

The development of microstructured optical fiber devices has been limited by the fact that these fibers are generally difficult, and in many cases even impossible, to fusion splice using conventional technologies. This is primarily because these fibers derive their unique waveguiding characteristics from fine air holes that are inevitably altered, even collapsed, by the high temperatures of conventional fusion splicing [1]. Moreover, index oil cannot be used to fabricate mechanical splices from such fibers since the oil induces loss by wicking into the air holes. As a result, most microstructured fiber experiments are performed with fibers that are free-space-coupled using bulk optics such as conventional lenses. Important advantages of fusion splicing over free-space-coupling include potentially lower backreflection, compactness, automatic and permanent alignment, and the absence of exposed optical surfaces that can be contaminated or damaged, especially by high optical power densities. Here we report on a new way of using gradient-index (GRIN) fiber lenses to achieve low-loss, high-strength, all-fiber fusion splices involving single-mode microstructured fibers. This technique is effective when splicing together two microstructured fibers, or a microstructured fiber to a conventional fiber, and is applicable to either air-core or solid-core microstructured fibers. This technique is important because it is effective even when the air holes of a microstructured fiber are completely collapsed in the vicinity of a fusion splice. Finally, the technique is quite flexible: a wide variety of microstructured fiber designs can be accommodated with a single GRIN fiber lens design.

The first documented fusion splices between microstructured optical fibers and conventional single-mode fibers exhibited relatively high losses (~1.5 dB at 1550 nm) [2]. Numerical calculations based on these early experiments suggested that splice losses as low as 0.2 dB could be achieved between such fibers at 1550 nm with suitable optimization of the fibers' design [3]. These early studies considered the effect of mode field diameter mismatch as well as modefield symmetry differences between conventional and microstructured fibers, whose modefields are typically axisymmetric and hexagonally symmetric, respectively. These studies did not, however, consider the significance of air hole collapse.

Conventional fusion splices are high-strength low-loss permanent joints fabricated by heating silica fiber tips to temperatures where surface tension overcomes viscosity, which can exceed 2000 C. At such temperatures surface tension will also act on the inside surface of a microstructured fiber's air holes and collapse them. However, by significantly reducing the duration and temperature of the fusion splice process, a fragile joint can be formed while minimizing collapse of the airholes [1,4]. Unfortunately, this joint will not exhibit the high mechanical strength characteristic of true fusion splice, which is typically greater than 100 kpsi stress (690 MN/m²). Since the long-term reliability of fusion splices has been linked to their mechanical strength [5], relatively fragile low-temperature microstructured fiber splices are expected to exhibit relatively poor long-term reliability. Another way to overcome hole collapse when fusion splicing microstructured fibers is to incorporate a doped-core that guides the mode even in the presence of collapsed air holes [6], but this significantly restricts microstructured fiber design.

2. The GRIN Fiber Lens Approach

Instead of striving to minimize hole collapse at the expense of splice strength and reliability, high-strength low-loss fusion splices can be fabricated from single-mode microstructured fibers with GRIN fiber lenses. A GRIN fiber lens is a relatively short length (200 μm to 2 mm) of gradient-index multimode fiber, whose refractive power is a function of its index profile and its length. This approach is directly analogous to free space coupling (Fig. 1), in

which the GRIN fiber lens is analogous to a bulk optical lens while the sections of microstructured fiber with heat-collapsed holes are analogous to free space.

Consider the evolution of a single-mode signal traveling from the fiber on the left to the fiber on the right in Fig. 1b. The fundamental mode of the microstructured fiber immediately begins to diffract when it reaches the point in the microstructured fiber where the heat from a nearby fusion splice has fully collapsed the air holes. This diffraction causes the beam propagating in the fully-collapsed region to enlarge and acquire phase curvature. Because the diffraction occurs inside pure silica, diffraction proceeds more slowly and with a lower diffraction angle than in free space. The GRIN fiber lens reverses the phase curvature of the diffracted beam, thus causing it to focus back down to a waist exhibiting a planar phase front and a spot size corresponding to the fundamental mode of the right-hand (receiving) fiber. When the receiving fiber is a conventional fiber instead of a microstructured fiber with collapsed air holes, a section of coreless pure silica fiber may be included to ensure proper modefield matching and efficient coupling. When coupling between single-mode fibers, the GRIN splice assembly is optically reciprocal, so the loss will be the same in either propagation direction.

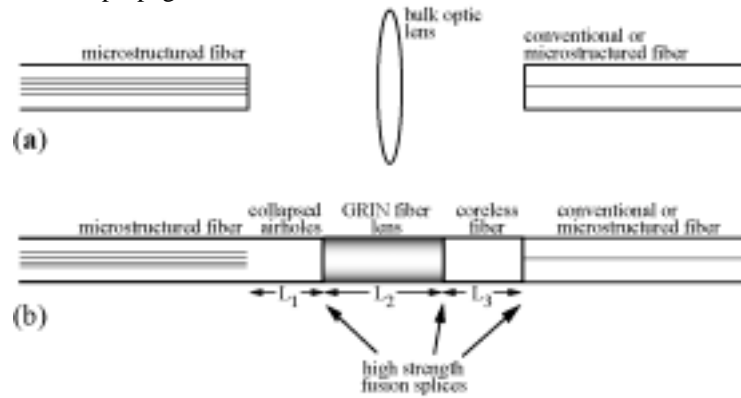


Fig.1. Illustration of how (a)conventional bulk optical coupling arrangement can be replaced by (b) GRIN fiber lens in conjunction with collapsed air holes in a microstructured fiber. When splicing together two microstructured fibers, the pure silica coreless fiber is replaced with a collapsed air hole region. Figure not to scale.

Complex arrangements of short segments of graded-index or coreless pure-silica fibers can be assembled together with conventional cleaving and fusion splicing technologies [7,8]. A wide variety of microstructured or conventional fiber designs can be accommodated with a single GRIN fiber design by tailoring the lengths of the GRIN fiber (L_2), the collapsed hole region (L_1), and a coreless pure silica sections (L_3). The added complexity of the GRIN splice approach, which requires a minimum of two fusion splices and four cleaves per connection, must be weighed against its loss and reliability benefits. The total length of the entire connection assembly will generally be less than 3 mm, which easily fits inside a conventional recoat or splice protector. The wavelength dependence of this GRIN fiber lens coupling scheme is comparable to that of conventional bulk optical coupling, since it is governed by the same phenomena (material dispersion and wavelength dependence of modefield size and shape).

3. Practical Limitations

Restricting the outer diameter of the GRIN fiber lens assembly to 125 μm leads to a minimum required modefield diameter (MFD) in the microstructured fiber. This is because a small MFD in a microstructured fiber will diffract rapidly in the fully collapsed region, expanding to a large diameter, and ultimately causing the optical signal to contact the fiber surface and exit the fiber. The maximum MFD occurs inside the GRIN fiber lens, so we can derive an approximation for the minimum permissible microstructured fiber MFD by modeling the optical propagation in the GRIN fiber lens assembly with the aid of the gaussian approximation.

The refractive index profile of the GRIN fiber lens, $n(r)$, can be written as

$$n(r) = n_0 \sqrt{1 - g^2 r^2} \quad (1)$$

where r is the radial position in the fiber, n_0 is the refractive index at the fiber center, and g is the focusing parameter. Since we are concerned with the limiting case where the beam diameter contacts the fiber surface, we require the graded-index region to fill the entire GRIN fiber lens cross section (no pure silica cladding). The practical limit for the refractive index contrast of a conventional doped-silica graded-index fiber is about 0.03. These facts can be combined with Eq. (1) to show that the focusing parameter, g , is limited to be less than or equal to about 3280 m^{-1} . The local mode field diameter of a gaussian beam propagating inside a GRIN fiber lens oscillates between a minimum MFD, $2\omega_{\min}$, and a maximum MFD, $2\omega_{\max}$, such that [9]

$$\omega_{\min} \omega_{\max} = \frac{\lambda}{\pi n g} \quad (2)$$

where λ is the vacuum wavelength. If we set $2\omega_{\max}$ to be the fiber diameter of 125 μm , and we use the strongest available focusing parameter, $g=3280 \text{ m}^{-1}$, we find that $2\omega_{\min}$ is about 3.3 μm . The actual minimum allowable MFD in the microstructured fiber is also a function of the length of the fully collapsed region, L_1 . When a high strength fusion joint is formed, the minimum length of the fully-collapsed region is typically about one fiber diameter, since the temperature field in the heated fiber tip cannot vary significantly over lengths shorter than a fiber diameter. The above estimate for the minimum allowable MFD in the microstructured fiber is in good agreement with more precise calculations using the gaussian ray-matrix approach [8], which revealed the minimum MFD to be about 3.5 μm .

In reality, the fundamental mode field of the microstructured fiber is not truly gaussian, as was assumed in the preceding discussion. Moreover, about 14% of the optical energy of a gaussian beam lies outside the MFD, so a crude estimate for the coupling loss when the maximum MFD contacts the fiber surface is about 0.6 dB. Lower coupling losses would require a larger MFD in the microstructured fiber.

4. Experimental Results

The 125 μm diameter silica-air microstructured fiber used in this study has an average hole pitch, A , of 5.3 μm and an average hole diameter, d , of $1.70 \pm 0.03 \mu\text{m}$. The fiber's mode field diameter at 1550 nm was estimated to be about 8.4 μm . Mechanically butt coupling this fiber to standard SMF (unspliced) yielded a loss of about 0.65 dB at 1530 nm, compared to a numerical prediction of about 0.55 dB. Optimizing conventional fusion splice conditions (no GRIN lens) between this fiber and standard SMF resulted in low splice temperatures and short splice durations. The optimized conventional fusion splice had minimal hole collapse, but was fragile, and exhibited a loss of about 0.9 dB, which is larger than the numerical or experimentally observed butt coupling loss.

Much better results were obtained with a GRIN fiber lens assembly as depicted in Fig. 1b. The graded-index portion of the 125 μm diameter GRIN fiber lens was 106 μm in diameter and had a focusing parameter, g , of about 2500 m^{-1} . Fig. 2b shows the local MFD predicted by gaussian ray-matrices when L_1 , L_2 , and L_3 in Fig. 1b are 345, 705, and 300 μm respectively. The discrepancy between predicted and the measured coupling loss, 0.1 dB vs. 0.5 dB respectively, may be attributed to imperfections in the GRIN lens, the transition region between the collapsed and un-collapsed air holes, and the non-gaussian nature of the true modefields. The typical failure strength of these splices was measured to be greater than 100 kpsi. Thus, the GRIN fiber lens approach had lower insertion loss than optimized conventional fusion splices, as well as higher mechanical strength and can thus be expected to exhibit superior reliability.

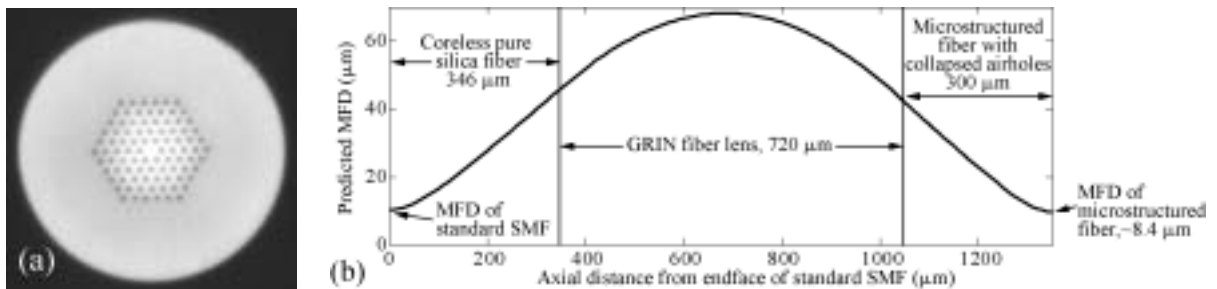


Fig.2. (a) End-on view of microstructured fiber, and (b) gaussian ray-matrix calculation of the local MFD for a signal propagating from standard SMF through a GRIN fiber lens fusion splice assembly into the microstructured fiber

5. References

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