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Laser Induced Damage Reduction in Single-Mode Fiber Devices[1]

F. Juárez López[a], F. Murtinez-Pinon[a], D. Jaramillo Vigueras[a], H. L. Offerhaus[b], and J. A. Alvarez Chavez[a,] *

[a] *Centro de Investigacion e Innovatión Tecnologica—Instituto Politecnico National, Cerrada CECATI S/N Col. Sta. Catarina, Del. Azcapotzalco, 02250, Mexico D.F., Mexico*

[b] *Optical Sciences Group, Twente University, Postbus 217, 7500 AE Enschede, The Netherlands*

*e-mail: jalvarezch@ipn.mx

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Abstract—We propose ihe use of tapered-up structures such as the fiber-horn lens and the straight-tip fiber-horn lens to be integrated in single-mode fiber devices to raise the damage threshold for input power. The optical damage limit with the use of such structures in single mode fibers is studied in this work. It is observed that for these devices to be practical, special attention needs to be put in the quality of the surface of the device and the quality of the fusion splice to standard single-mode fibers. New studies, techniques and fiber splicing equipment should help the new structures studied here, inwards their implementation in all-optical devices and high-power fiber lasers.

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1. INTRODUCTION

Single-mode liber taper structures have been studied extensively because they offer a self-aligned approach to beam expansion within the fiber [1]. These single-mode fiber beam expanders behave as lenses. There are two typical forms of fabricating single-mode fiber tapers: “taper-down” and “taper-up.” In each case, adiabatic expansion of the fundamental mode needs to be observed in order to avoid mode conversion [2]. “Taper-down” devices can be fabricated by simply pulling a cladding-stripped single-mode fiber within a heat source. An improved technique consists of an over-jackcted fiber device [3]. A taper-up device such as the fiber-horn lens structure can be constructed by taking advantage of the taper present in the geometric transition from preform to fiber when the normal drawing process is stopped [4]. Figure 1a is a schematic of one such taper with its typical conic shape. In practice, for this taper device to work, the refractive index of the profile has to be a step which in the modified chemical vapor deposition (MCVD) process can only be obtained if the core is made of pure silica and the cladding is depressed via boron doping, for example, as shown in Fig. 2b.

The requirement of the step index profile for the fiber-horn lens was experimentally determined as an ordinary MCVD profile with a dip in the middle of the profile produced an uneven beam expansion. In a normal fiber the dip is a traction of the wavelength and it is averaged in an equivalent step index (ESI) [5]. However in a beam expander as the one we constructed with the wavelength now being a fraction of the size of the dip, the refractive index profile is not longer averaged and the optical field distribution of the single mode fiber “follows” the shape of the refractive index profile. The fiber horn lens is not a single-mode waveguide but rather a highly multimode waveguide in which only the fundamental mode has been excited by an adiabatic transition.

The second taper-up device is manufactured in a two steps process involving a pure silica-core preform [6–8]. In step 1 thin preforms from approximately 0.6 up

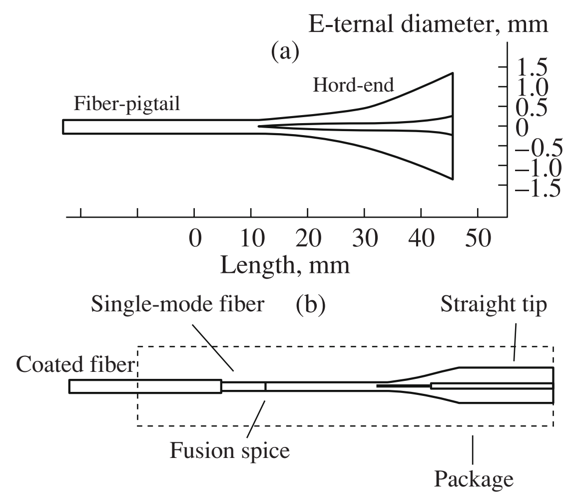

Fig. 1. Schematic of tapered-up structures: (a) Fiber-horn lens and (b) straight-tip fiber lens showing its construction.

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to 1.0 mm are produced. Then in step 2, the thin preform is pulled in a small graphite furnace to a diameter similar to that of a standard single-mode fiber of 125 μm. The magnifications obtained for a fiber-horn lens and straight-tip single-mode fiber taper are 10× and 4× approximately.

Laser induced damage of optical fibers and crystals, has been widely studied. The fiber fuse effect (catastrophic destruction of optical fibers) that occurs at relatively low continuous wave (CW) optical power (less than 1 W) was observed and described in 1988 by Kashyap [9]. Since then several researchers have studied the subject [10–12]. As the amount of launched power into a single mode fiber (-device) power is increased, a threshold is found over which the entrance is catastrophically damaged.

Fiber end facets are damaged by *pulsed* optical power when peak powers of the order of a few kilowatts are launched. Damage occurs in single-mode fibers at the entrance face. Power damage is a statistical process [13], and depends on many factors. Two of the main factors that influence the damage threshold are: (1) The optical power density focused in the core of the single-mode fiber and (2) the preparation of the surface of the fiber entrance face. The damage threshold measured by Buzhinski [14] for several "fiber optic elements" has a large range of variation: from 162 to 388 J/cm^2, for λ = 1.06 μm and pulse duration of 4×10^{-8} s. However, from this data power damage threshold could be estimated to be in the range of 0.64–3.79 kW for a single-mode fiber with parameters, $V = 2.3$, $NA = 0.11$ and core radius $R_c = 3.5$ μm operating at the same wavelength.

In principle, it is possible to raise the damage threshold of an optical fiber with single-mode fiber lenses. A larger core at the fiber entrance face results in a smaller power density for the same optical power. Alternatively, for the same power density that produces damage, the total power that can be launched with a fiber lens would be higher than in a single-mode fiber without fiber lenses, the improvement being equal to the square of the beam expansion factor. For instance, a ×5 fiber lens would represent a 25 times improvement in total power launched. Avoiding or reducing the risk of laser induced damage in the fibre is important in practical applications of laser ablation, laser marking, tattoo removing, optical power delivery for machining applications [15] and Q-switched Nd:YAG lasers [16]. We propose here, the use of tapered-up self-aligned single-mode fibre lenses to launch the optical power into the single-mode fiber or single-mode fiber device. In this manner, the relatively large area at the entrance face of the taper should reduce significantly the power density and therefore, the risk of catastrophically damage of the device.

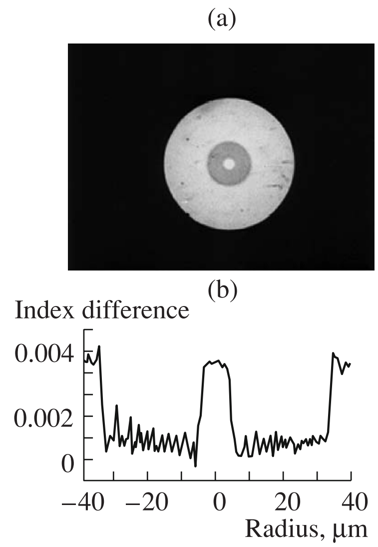

Fig. 2. Pure silica-core fiber used in the fabrication of the fiber-horn lenses (a) photograph of the cross section and (b) refractive index profile.

2. EXPERIMENTAL SETUP

The experimental setup consisted of an Nd:YAG laser (operating wavelength: 1.06 μm) launched into the standard single-mode fibers, the (broad) horn-end or straight-tip end of the fiber device. The laser was operated in Q-switched, mode-locked configuration. The optical pulses obtained had 500 ps duration with an envelope having a FWHM of 180 ns and a repetition rate of 1 kHz. The magnitude of the peak power of the pulses was varied from 500 W to 4 kW.

For the liber horn lens, a pure silica-core preform was fabricated in house by the MCVD process. A photograph of the cross section of the fiber is shown in Fig. 2a and its refractive-index profile in Fig. 2b. The depressed cladding was obtained by doping with boron. The index difference is approximately 0.004 (NA = 0.1). The diameter of the fiber pigtail was chosen to give single-mode operation at the required wavelength, the normal pulling operation was stopped and the preform was cut at a point where its external diameter was approximately 2 mm. The fiber pigtail of the fiber horn lens can be of any length; however, it is obtained without a protective coating. A 2-m long pigtail was preferred for handling the device for mode field radius measurements.

For the straight tip fiber horn lens, another pure silica-core was fabricated. However, this time the boron doped depressed cladding resulted in an elliptical shape as shown in Fig. 3.

3. RESULTS AND DISCUSSIONS

The average damage threshold for three standard single-mode liber samples at λ = 1.06 μm was approximately 3.5 kW (peak power). Conic fiber-horn lenses

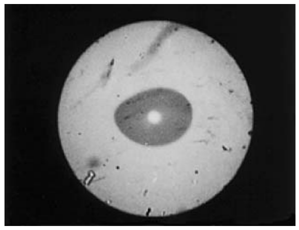

Fig. 3. Pure silica-core fiber used in the fabrication of the straight-tip fiber horn lens.

having an approximate beam expansion of ×10 and fiber pigtails between 1 and 2 m in length were used to transmit optical pulses from a Nd:YAG laser, as discussed previously. The transmitted power was measured at the fiber-pigtail end. There were no splices. Figure 4a is a photograph of the laser-induced damage at the horn end of the fiber horn lens. Figure 4b is the same horn end with the damage made invisible by the addition of a drop of index matching oil. The circular dark area shown in Fig. 4a corresponds to the depressed-inner cladding region surrounding the core. The bright circle in Fig. 4b is the core at the horn end. The core diameter is 88 μm. A comparison of the photographs indicates the extent of the damage which includes the core and some of the surrounding region.

The magnitude of the peak power necessary to induce laser damage at the horn-end was 600 W and is smaller than in untapered single-mode fibers. The low damage threshold can be attributed to the low quality of the surface of the horn-end, which was only coarsely polished. Obtaining high-quality polished surfaces proved very difficult with conic fiber-horn lenses because of handling problems of the device, as a consequence of their conic geometry and uncoated fiber-pigtails. For this reason, attention was turned to straight-tip fiber horn lenses for this application and further work on conic fiber-horn lenses will be done in the near future.

Straight-tip fiber-horn lenses spliced to a single-mode fiber at $\lambda = 1.06$ μm were tested for high-power launching. The magnification of the straight-tip lenses was in the range ×3 to ×5. The external diameter of the straight-tip was between 0.6 and 1.0 mm. The straight tip was hand cleaved, which gives room for optical quality improvement with new cleaving devices. The quality of the surface provided with the cleaving was such that further polishing was not required. The magnitude of the peak power needed to induce damage in the straight-tip fiber lens was approximately 4 kW. This value is several hundred watts larger than the damage threshold observed in untapered single-mode fibers. The damage did not occur at the horn end but at the splice. Figure 5a is a photograph of the splice between the single-mode fiber and the fiber lens. Damage seemed to have originated at the splice and propagated backwards to the horn end of the fiber lens. The damage was produced mainly in the core and stopped at a point between the splice and the horn end as in Fig. 5b. The fact that for the straight-tip fiber-horn lens damage originated at the splice and not at the entrance end face indicates that the quality of the splice is very important for

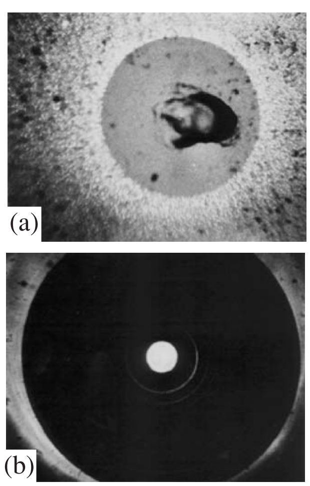

Fig. 4. (a) Photograph of laser induced damage in a conic fiber-horn lens. The dark circular area is the depressed inner cladding (b) Photograph of the same fiber lens with index matching oil. The core is the bright circle and its diameter is 88 μm. The photographs have not been taken at the same magnification.

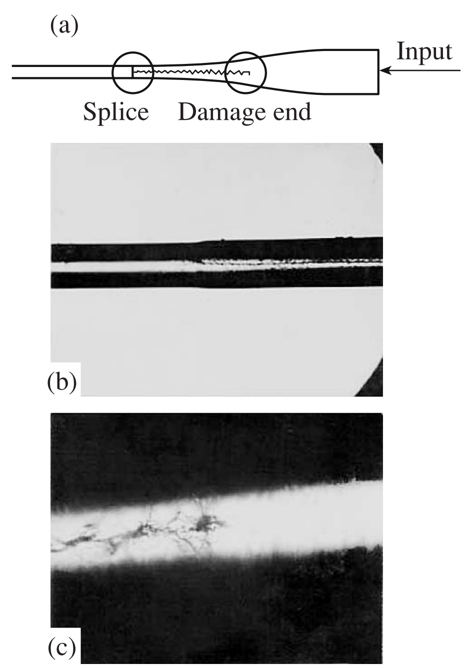

Fig. 5. (a) Schematic of the laser induced damage in the straight-tip fiber-horn lens. (b) Photograph at the splice. (c) Photograph of the region where the damage stopped.

the power handling capacity of the device. It is suspected that impurities and defects absorb optical power and thereby trigger the damage by lowering the heal capacity handling of cylindrical waveguides such as optical fibers.

4. CONCLUSIONS

We have demonstrated two possibilities of using tapered structures to raise the damage threshold in single-mode fibers and fiber devices. The first is the fiber-horn lenses which can have a magnification factor of up to ×10. This structure requires special attention to the quality of the surface which should be very well polished to avoid beam distortion and it has the minor disadvantage of its conic shape. The latter can be solved by designing a specific holder which can be straightforward to make in addition to the relatively low sensitivity to angular, lateral and axial misalignment. The second possibility is the use of straight-tip fiber-horn lens which can be cleaved instead of polishing. The magnification factor obtained was around ×4 and the damage was not in the entrance facet but in the splice in a manner similar to the fiber fuse initiated by a hot spot. It is believed that further refinements in the construction of these devices will allow for larger optical power input before catastrophic damage is produced.

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