Single-mode delivery of 250 nm light using a large mode area photonic crystal fiber

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Single-mode delivery of 250 nm light using a large mode area photonic crystal fiber

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Abstract: We demonstrate that large mode area (LMA) photonic crystal fibers (PCFs) can be used as single-mode patch-cords for 250 nm laser light. We have studied the transmission of the 250 nm output beam of a frequency-quadrupled diode laser through a triangular structure LMA PCF with 10 μm core. We have achieved single-mode output with coupling loss of 1.8 ± 0.6 dB and transmission loss of 1.5 ± 0.2 dB/m. The critical bend loss radius is approximately 6 cm. The transmission loss is compared with published bulk silica measurements. Effects of optically induced damage were observed after prolonged operation and have been studied as function of laser power and time. The optical damage occurs primarily at the fiber input and can be partly ameliorated by cleaving the fiber input. For input power levels of <~0.3 mW stable operation can be achieved for periods of >40 hours which is sufficient for many laboratory based applications. The results show the utility of these fibers for single-mode beam delivery in a spectral region where step-index single-mode fibers are not readily available.

OCIS codes: (060.2270) Fiber characterization; (060.2430) Fibers, single-mode; (060.5295) Photonic crystal fibers

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1. Introduction

Single-mode delivery of ultraviolet (UV) light by optical fibers is desirable in many scientific applications requiring high beam quality. Long operating times are desirable but, as is further discussed below, in many applications shorter durations are acceptable (e.g. 1s-10s of hours). In contrast to communications, in many scientific applications it is necessary to deliver the light over relatively short distances (~1-10 m), i.e. to use the fiber optic as a patch-cord. The choice of available waveguides for this purpose is limited. In terms of widely available single-mode silica step-index fibers, the shortest cutoff wavelength is ~300 nm with core diameter of ~2 μm. Single-mode behavior can be considered in terms of the fiber's V parameter (dimensionless frequency), $V=(2\pi/\lambda)\ a\ NA$, where λ is the wavelength of light, a is the core radius, and NA is the numerical aperture. For single-mode operation one requires $V<2.405$. In principle, a lower cutoff wavelength could be achieved by either reducing the NA at fixed core dimension, or vise versa. In the former case bending losses increase, while in the latter case coupling of light into the small core is difficult, and nonlinearity and UV damage must be considered. For example, Bartula et al. [1] used a commercial single-mode fiber at 337 nm, but the core diameter of ~2 μm limited the coupling efficiency to <~10% owing to the difficulties of achieving diffraction limited spot sizes. (The exact coupling efficiency was not given in the aforementioned work, but the overall efficiency was 4% with a transmission loss of ~40-70 %.)

In some cases one can circumvent the normal V-parameter limits of convention step-index fibers. By employing large mode area (LMA) approaches, single-mode propagation is achieved in (nominally) multimode fibers by suppressing the mode-coupling to higher order modes. One approach has been demonstrated with stable fiber coupling and large diameter fibers [2], but because mode coupling strongly increases for short wavelengths may not be directly applicable for the wavelengths of our interest. An approach widely used in fiber lasers involves coiling the fiber [3], though for passive fibers the coiling reduces the fiber transmission [4].

Here, we consider the use of photonic crystal fibers (PCFs) for single-mode delivery of UV wavelengths in the range ~200-300 nm. Typical PCFs have a uniform patterned microstructure of holes (defects) running axially along the fiber channel with a missing hole in the center providing a core region. In an equivalent index-of-refraction picture, the microstructure imposes a strong wavelength dependence on the index-of-refraction of the cladding, and for high light frequencies (short wavelengths) the cladding index approaches the core index. With appropriate fiber design, the fiber core can support a single guided mode over all optical frequencies, a characteristic referred to as endless single-mode operation. For triangular, high-index core PCFs with circular hole defects, endless single-mode operation is achieved for $d/\Lambda <\sim 0.4$, where d is the hole diameter and Λ is the lattice spacing [5]. A useful feature of these fibers is that the endless single-mode characteristic can apply even for relatively large core dimensions (for which step-index fibers would be multimode) in which case they are termed LMA PCFs. A common use of LMA PCFs is to deliver high-power visible or infrared pulses, e.g. within fiber lasers.

In principle, the fiber properties also allow single-mode delivery of short wavelengths that are below the cutoff of standard step-index fibers. To the best of our knowledge, this contribution is the first report of single-mode delivery of laser beams in the 200-300 nm range using LMA PCFs. The loss of the silica material limits long distance delivery, but we show that the fibers can be used as patch-cords over distances of <~10 m.

Optical damage of silica by UV photons also provides a practical impediment to fiber delivery in this wavelength range. We have observed such effects in our experiment which, depending on laser power, lead to damage (reduced transmission) after 1s-10s of hours. Clearly these durations preclude use in long-term applications (e.g. communication links), but they are sufficient for many laboratory based experiments that critically require fiber optic delivery. For example, we are implementing cavity ring-down spectroscopy (CRDS) within vacuum chambers to study boron sputtering from electric propulsion thrusters [6]. A measurement campaign to study several thruster operating conditions requires approximately 1 hour. In these experiments the laser must be kept outside the chamber and single mode fiber delivery is critical to allow precise and stable alignment of the beam to the high-finesse optical cavity within the chamber. (Passing the beam through chamber windows is very impractical since even small displacements from thermal expansion, or vibration from vacuum pumps, leads to misalignment of the optical cavity.) Similarly, other UV laser based diagnostics, e.g. UV laser induced fluorescence of biological matter such as aromatic amino acids [7], cavity enhanced spectroscopy of processing plasmas [8], combustion studies of soot [9] or greenhouse gas species [10] etc. could all potentially benefit from single-mode fiber delivery even if over relatively short distances and durations. This is especially true when such measurements are made in environments unsuitable for open-path (free-space) delivery, for example within vacuum chambers, between moving or vibrating components, within combustion environments where beam steering or absorption or scattering may be problematic etc. In some cases pulsed lasers are currently used, but the use of single-mode fibers with continuous-wave lasers can be useful in these or similar experiments, for example to improve spatial resolution or detection limits.

2. Experimental setup for fiber coupling

The setup used in our fiber testing is shown in Figure 1. The light source is a frequency-quadrupled diode laser system (Toptica TA-FHG 110) operating at 249.7 nm (for resonance with boron absorption). The laser has linewidth of ~5 MHz and output power of 12 mW though the power at the fiber input was ~1 mW. The laser output beam is astigmatic and a cylindrical lens near the laser output is used to roughly collimate the laser output. The laser output is close to single-mode but a spatial filter is also used. In some experiments the beam is also passed through an acousto-optic modulator (prior to the spatial filter) as part of a setup for cavity ring-down spectroscopy, but the AOM does not appreciably affect the results presented here. The fiber launch was designed to modematch the beam to the fiber input and uses a plano-convex quartz lens (f=50 mm) for free-space coupling to the fiber. The fiber is mounted in a V-groove fiber holder on a precision 5-axis stage. We use LMA PCFs with core diameter of ~10 μm (Crystal Fibre LMA-10 UV). These fibers are optimized for ultraviolet and visible operation [11]. The fibers have a single cell triangular structure with lattice spacing (pitch) of 6.26 µm and hole size of 3.04 µm (d/Λ=0.485). Modeling shows these fibers to be endlessly single-mode with the relatively large d/Λ value mitigating the bending loss edge at short wavelengths, to promote UV operation. The overall cladding diameter is ~230 µm. For 250 nm operation, the fiber NA and mode field diameter (MFD) are estimated as ~0.03 and ~8 µm respectively. We have done some measurements with end-sealed fibers, but results reported here are primarily for unsealed fibers. The endfaces have been cleaved but not prepared in other ways.

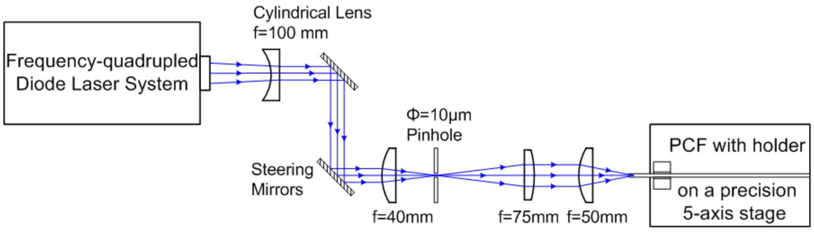

Figure 1. Schematic diagram of fiber launch

Figure 2 shows a photograph of the fiber output incident on a card several cm downstream of the fiber exit. The shape of the beam pattern is typical of single-mode output from a triangular PCF [12]. Single-mode output was also confirmed in several ways. First, we checked power transmission through a downstream pinhole. We used a first lens to collimate the fiber output to diameter 0.8 mm and then a second lens of focal length 45 mm to focus the light through a pinhole. In this way, we could transmit more than 90% of the power through a 30 µm pinhole. Second, we have mode-matched the fiber output to a high-finesse CRDS optical cavity and coupled the light predominantly to the fundamental longitudinal cavity modes (higher order modes exiting the fiber would couple to higher order cavity modes). Finally, as shown in Figure 3, we have used a Spiricon beam profiler (SCOR20) to measure the M^2 of the light exiting the fiber (length1.3 m). The output beam was weakly focused using a plano-convex lens (focal length 200 mm) and the dependence of beam diameter on position resulted in M^2=1.08, confirming (near) single-mode output. When the fiber launch was misaligned, we could still couple power through the fiber but the output did not appear single-mode and the NA tended to be lower. In these cases, light was presumed to be transmitted through the cladding. The fiber coupling was also very sensitive to mechanical conditions. Over-tightening of the spring-loaded *V*-groove could degrade the 249 nm delivery (both efficiency and output mode), while having no appreciable effect on 633 nm delivery, due to micro-bending losses [13].

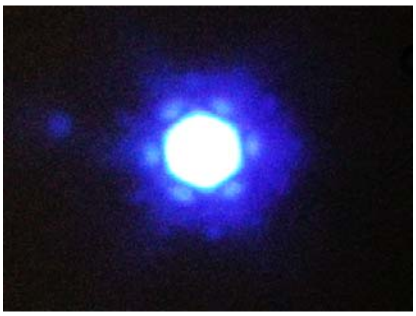

Fig. 2. Photograph of single mode fiber output. The image is saturated in the center region.

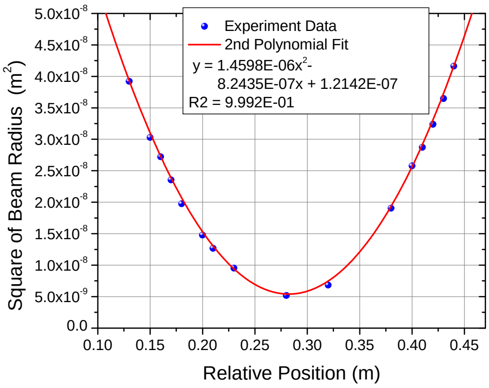

Fig. 3. Beam dimension versus position for M^2 determination.

3. Fiber transmission

Rather than performing a cutback test, we studied the fiber coupling and transmission loss by measuring the power transmission for fibers of several lengths. Figure 4 shows the results for fibers of length 0.45-4 m. The power at the fiber input was ~1 mW. For testing for fiber lengths of <3m the fiber was held relatively straight, while for testing for lengths of >=3m the fiber was moderately bent with radius-of-curvature of roughly 0.5 m. Fiber bend loss is further discussed below. The transmission data are reasonably fit (*R*=-0.96) with a straight-line of intercept -1.8 ± 0.6 dB and slope of -1.5 ± 0.2 dB/m, corresponding to a coupling loss of ~34% and transmission loss of ~29% loss per meter. The scatter in the data may be due to optimization of alignment for each fiber, but is also likely related to optical damage discussed below. The coupling loss is reasonable for single-mode coupling at these short wavelengths, though some optimization may be possible with better mode-matching (e.g. reduction of aberration or improved combination of launch lens and beam diameter). The transmission loss can be converted to a (Beer's Law) absorption coefficient of a_λ=0.35 ± 0.05 m^{-1}. To find the corresponding absorption index (imaginary component of the index-of-refraction) k_λ, we use $k_\lambda=(\lambda/4\pi)a_\lambda$ where λ is the (free-space) wavelength, and find k_λ= (7 ± 1) x 10^{-9}. The value is somewhat low relative to published values for silica glass [14], but there is considerable scatter and uncertainty in these measurements owing to the type of silica (natural versus synthetic), impurities, and measurement method (e.g. transmission based measurements cannot adequately resolve small losses). Another comparison can be made with extrapolation of the fiber data-sheet [11] using a λ^{-4} scaling (i.e. assuming loss is dominated by Rayleigh scattering) which gives ~0.25 dB/m (k_λ=1.2x10^{-9}) indicating that there is an additional absorption contribution, likely from impurities (e.g. Cl) and micro-bending.

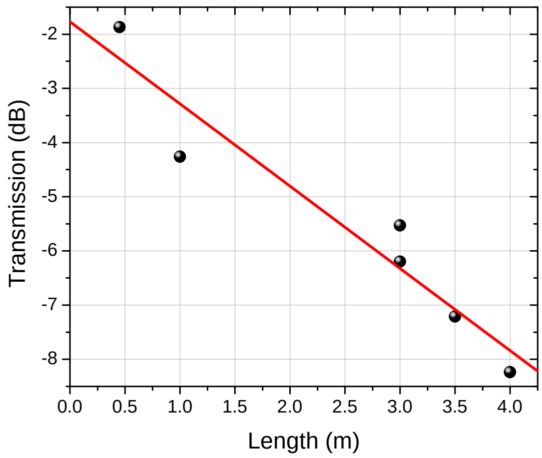

Fig. 4. Loss measurements: Plot of fiber transmission versus fiber length.

We also considered fiber bending loss. Fiber transmission was measured for a fiber with a single-loop (360° of bending) of different curvatures. The upstream and downstream segments of the fiber were held approximately straight. The bend loss results are shown in Figure 5 and are determined based on the additional transmission loss caused by bending. We find a critical bend radius of approximately 6 cm.

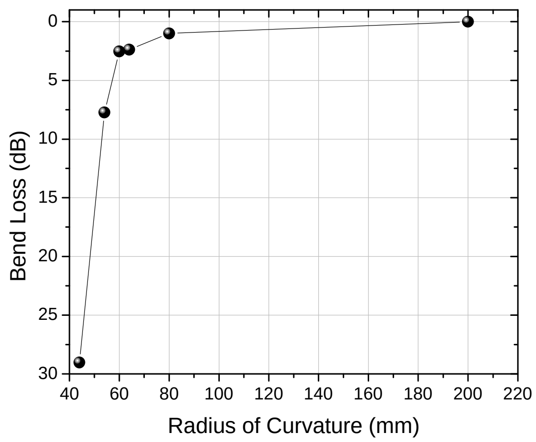

Fig. 5. Bend loss measurements: Plot of bend loss versus radius of curvature.

4. Optically induced damage

The transmission results of Figure 4 are maximum values obtained after fiber alignment. After prolonged operation the fiber transmission was reduced due to radiation-induced defects, i.e. color centers or solarization. Past studies involving irradiation of fused-silica (bulk samples and multimode fibers) by krypton fluoride (KrF) lasers at 248 nm found optical damage attributed to *E'* centers, i.e. an unpaired electron in a silicon dangling bond (absorption centered at ~210 nm), or nonbridging oxygen hole center (NBOHC), i.e. an unpaired electron in an oxygen dangling bond (absorption centered at ~265 nm) [15, 16].

Our observations are consistent with these studies as the 250 nm irradiation reduced transmission at that wavelength, while transmission of 633 nm light is not affected [15, 16, 17, 18]. Additionally, as shown in the left of Fig. 6 we observe that the damage is accompanied by red fluorescence from the fiber tip [15, 19].

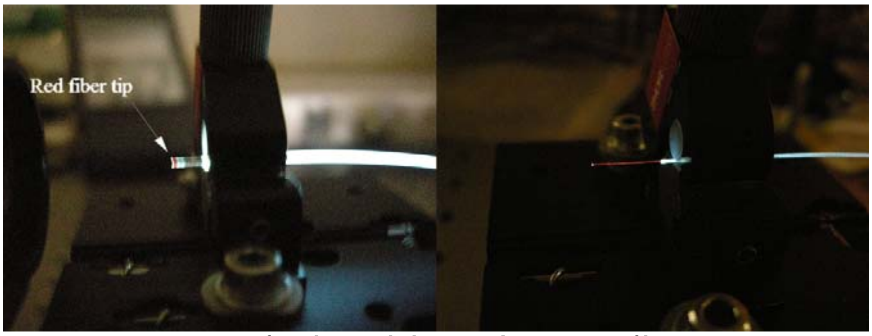

Fig. 6. Left: Photograph showing red emission near fiber tip.
Right: Photograph showing red emission over length of fiber.
The jacket of the fiber has been removed at the fiber end.

Several studies were performed to characterize the optical damage. Figure 7 shows the power dependence of the optical damage. The transmission data are for (previously) unused fibers of length 1.3 m and the plotted transmissions are normalized by the initial transmission (approximately 45%). The short timescale fluctuations of each transmission curve are owing to small drifts in laser power or input alignment (both of which were periodically monitored and corrected). Higher optical power leads to more rapid damage but the damage is not simply dependent on the overall fluence. Operation with input power of 0.3 mW leads to an initial drop followed by stable operation over more than 40 hours at about 65% of the initial transmission. Similar UV damage characteristics with differing short- and then long- term behaviors (slopes) have been reported in commercial silica fibers [20]. As discussed in the introduction, operation for 1s-10s of hours, as demonstrated here, is useful in several applications. There has been some discussion on the possible role of two-photon processes in the damage [15, 17] but the low powers used in our experiment suggest this to be unlikely.

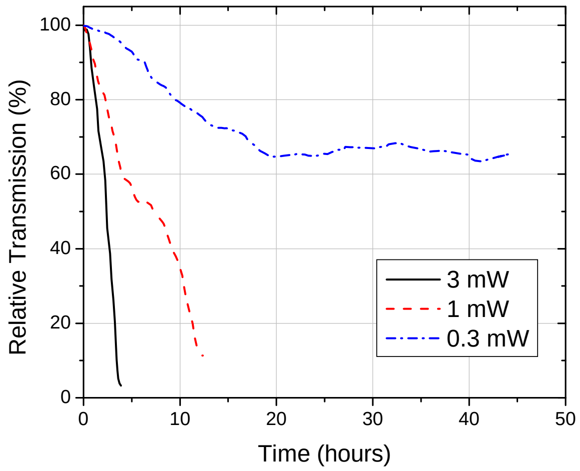

Fig. 7. Power dependence of optical damage.

The transmission data of Fig. 8 shows partial recovery of fiber transmission after cleaving the fiber input. Again, the transmission data are normalized by the fiber transmission at the start of the first test. The fiber (previously used) had starting length of 4 m and the input power was approximately 3 mW. A standard commercial cleaver (Fujihura CT32) was used to cleave the fiber input tip (~1 cm) after the relative transmission reached approximately 10%. Cleaving the tip partially restored the fiber transmission likely related to damage occurring predominantly at the input tip as discussed in connection with Fig.6. The test results of Fig.7 did not include any cleaving, and cleaving therefore provides a means to somewhat extend fiber lifetime; however, the reduction in transmission after successive cleavings (i.e. to about 85% after the first cleave and about 75% after the second cleave) is indicative of a longer term damage process occurring in the length of the fiber which ultimately leads to end of fiber life.

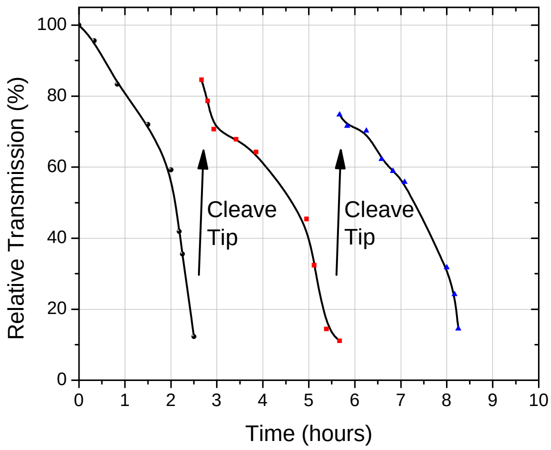

Fig. 8. Effect of cleaving fiber input tip on optical damage.

5. Conclusion

We demonstrate that LMA PCFs can be used as patch-cords for short distance single-mode fiber delivery of 249 nm light. The capability is important owing to the lack of fiber options for single-mode delivery in this wavelength range. Single-mode fiber output has been verified and launch losses and transmission losses examined. For prolonged operation, optically induced damage has been observed. While the damage would be problematic for long term operation, we are still able to operate the fibers over time periods useful in many experiments. By periodically cleaving the fiber tip and/or using low laser powers, durations of 10s of hours (and perhaps longer) are possible. Alternative fiber designs may obviate the optical damage but the large core (low intensity) and undoped glass used in the LMA PCF are already favorable from this point of view.

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