Measurement of far-ultraviolet transmission in hollow-core optical fibers

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The fabrication of optical fibers for the ultraviolet regime is hindered by the poor transmittance of most optical materials in this spectral range, which is often further degraded by exposure to these highly energetic photons. Hollow-core anti-resonant optical fibers are predicted to achieve much lower losses than those observed in solid core and photonic bandgap fibers. We have measured optical guidance in hollow-core fibers over the spectral range of 120 – 200 nm. These UV hollow-core fibers (UV-HCFs) promise to enable the versatility already afforded by conventional fibers in the visible and infrared regimes.

UV HOLLOW-CORE FIBERS

Hollow-core anti-resonant fibers are made entirely of fused silica and are characterized by a hollow guiding region surrounded by a ring of capillary “resonators”, which are supported by a thick silica cladding (Figure 1). These fibers guide light in spectral regions between high loss locations, which correspond to resonances, *m,* found at

$$\lambda_m = (2t/m)\sqrt{n^2 - 1}, \qquad (1)$$

where *t* is the capillary wall thickness and *n* is the refractive index [1].

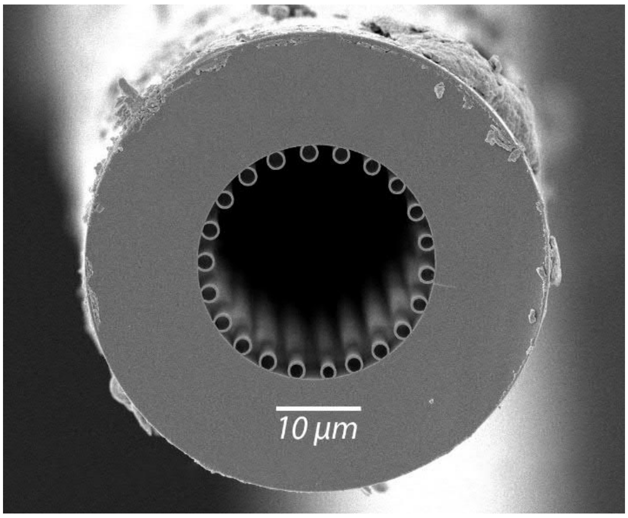

Figure 1. The fibers we fabricated and measured as part of this work are made of fused silica, with a ~25 μm diameter guiding region and 22 resonators.

Because the refractive index of silica increases rapidly for $\lambda < 200$ nm, the capillaries must be extremely thin. To achieve this thickness, fibers are first fabricated using the stack-and-draw method and then tapered [2] with a draw-down ratio of ~7:1. The resulting fibers have an OD of ~50 μm and a guiding region of ~25 μm diameter. This first round of samples had a length of ~20 cm; longer fibers can be made by modifying the tapering rig.

MEASURING FUV FIBER TRANSMISSION

Traditional techniques to measure optical fiber transmission are not easily adopted for the vacuum ultraviolet spectral range, for a number of reasons:

1) Conventional fiber launch systems, which employ microscope objectives, cannot be used to couple light into the fibers in a controlled manner. Neither can these fibers be “butt-coupled” to other “source” fibers.
2) The relatively short length of the sample fibers used in this experiment makes the cut-back method of determining fiber losses difficult.
3) Oxygen strongly absorbs light with $\lambda < 185$ nm; this is especially problematic for an experiment employing “free space” optics.

To measure the UV transmission of these fibers, we developed a measurement apparatus (Figure 2) that could be purged with nitrogen, to minimize the transmission losses due to oxygen absorption. In the remainder of this section, we describe our measurement methodology.

First, the sample fiber was cleaved to obtain a clean edge on both ends; the quality of the cleave and the ability of the fiber to guide visible light were verified using a microscope. Next, to remove any air or water vapour from the hollow core and capillaries, the fiber was placed in a vacuum chamber, which was pumped down to ~10^{-5} Torr. The chamber was then back-filled with nitrogen and brought up to atmospheric pressure.

Next, the fiber was placed into a v-groove plate on a translation stage, which aligned the output end of the fiber with the entrance slit of an ARC VM-502 UV monochromator. The input end of the fiber was aligned with the output of a deuterium lamp with a MgF_2 window. The lamp output was stopped-down with a 3 mm diameter aperture to produce a ~f/25 outgoing beam; the numerical aperture of these fibers corresponds to a beam of ~f/12; *i.e.* the input beam is well within the fiber's NA. Light from the fiber was dispersed by the monochromator and measured by a photomultiplier tube (PMT) detector. The spectral bandwidth of the outgoing light was $\Delta\lambda \sim 2$ nm.

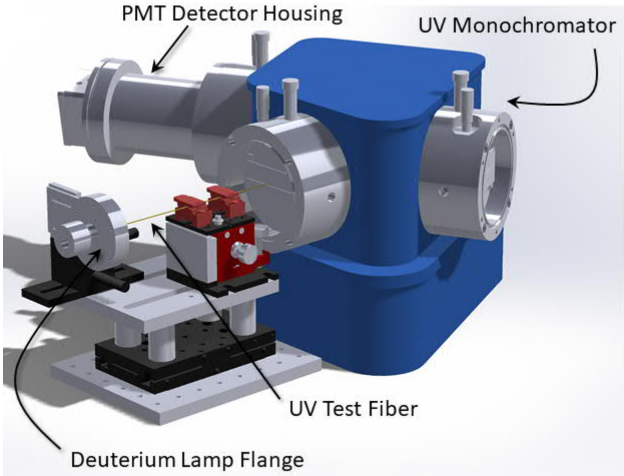

Figure 2. The setup that was used to measure the UV transmission of the hollow-core fibers was designed with an enclosure (not shown here) which allowed us to purge the entire setup with nitrogen.

We took great care to measure any background signal that could be mistaken for light transmitted by the fiber. When the fiber tip was illuminated, it extended ~2 mm into the 3 mm aperture. To measure any stray light, we bent the fiber tip out of the aperture and rested it against the aperture plate. In this way, the entire setup was minimally changed, but the fiber tip was moved completely out of the beam.

PERFORMANCE OF UV FIBERS

Due to the complexities associated with working the FUV regime, in this experiment we were unable to perform the cut-back method to quantify the fiber's transmission. Instead, we compared the fiber's throughput to that of a 25 micron pinhole. Using a CCD camera, we measured the divergence of the light beam exiting the pinhole to be ~f/60. Therefore, we are confident that all of the light from the pinhole, and the fiber, was captured by the f/4 focusing diffracting grating of the monochromator and detected by the PMT. The resulting throughput of one of our fibers, normalized to that of a 25 micron diameter pinhole, is shown in Figure 3.

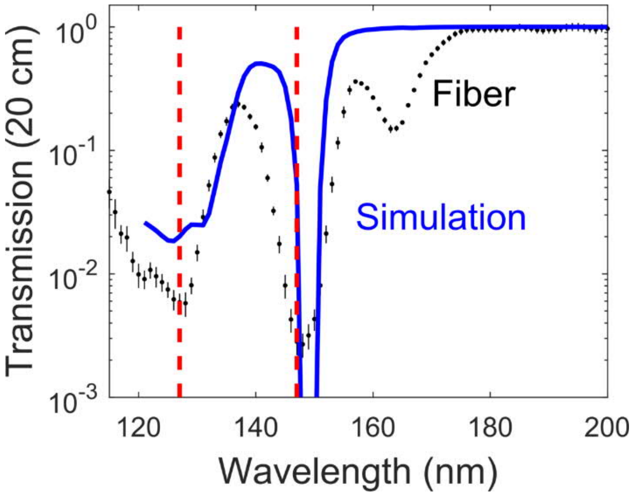

Figure 3. The throughput of the UV hollow-core fiber, with respect to that of a 25 micron diameter pinhole, is shown, along with predictions from a numerical simulation for a fiber with a similar physical structure. The dashed red lines indicate the resonance locations given by Eq. 1.

After the fiber transmission was measured, the shape and thickness of the capillary resonators was determined using scanning electron microscopy. Using the measured structural parameters, we simulated the performance of this fiber using COMSOL Multiphysics. The simulated performance and the measured throughput are similar (Figure 3).

CONCLUSION

We have shown that hollow-core anti-resonant fibers can guide light in the far-UV spectral regime, down to ~130 nm, with sufficient throughput to be useful in a wide range of applications. This shatters the current wavelength limit for UV fibers, of ~185 nm. Furthermore, the fiber's performance agrees well with results of numerical models and analytic predictions. By tuning the locations of the resonances, it should be possible to fully cover the 100 – 200 nm FUV spectral regime with hollow-core UV fibers.

REFERENCES

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