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680 hrs endurance test of a DUV laser beam delivery via a connectorized hollow-core photonic crystal fiber

Paper #

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Introduction

Abstract

Laser beam delivery is crucial in fields like surgery, micromachining, spectroscopy and scientific applications. Hollow-core photonic crystal fiber (HCPCF) technology, with its exceptional energy and power handling, is becoming a recognized component in several industries. However, this maturity and industrial adoption have been thus far limited to the infrared and visible spectral ranges. For instance, the UV and DUV ranges have been scarcely addressed and remain a challenge for laser beam delivery due to chemical and physical alteration of most solid materials when exposed to light whose wavelength is below 300 nm. This technology gap in UV light beam delivery contrasts with the ever growing need for UV lasers to be delivered to the work piece in a safe, flexible and cost-effective manner.

In this communication, we report on the development of inhibited-coupling HCPCF (IC-HCPCF) with record transmission losses inferior to 50 dB/km at 266 nm and solarization-free. A 2 meter-long sections of this IC-HCPCF are then mounted into SMA termination patchcords for UV power handling and life-span tests. A laser beam of a 266 nm wavelength laser-source, emitting 1 ns wide and 37 μ J energy pulses, was coupled into the IC-HCPCF patchcord, reaching a total transmission rate of 93%. Finally, the laser beam was kept continuously coupled into the patchcord for over 680 hrs. The results show excellent stability of the transmitted power (fluctuations of less than 5 %), as well as the fiber output mode quality. To our knowledge this is the first fiber guidance of DUV laser that combines high energy handling and long lifespan. The results mark a major milestone in the adoption of fiber UV laser beam delivery by the industrial community.

Silica solid-core optical fibers are recognized as a major key in the development of the optical telecommunications network working by total internal reflection (TIR) mechanism. These fibers have achieved ultra-low transmission losses in the infrared range, with a record of 0.1419 dB/km at 1550 nm, within the transparent spectral window of silica [1]. However, silica has limitations that affect the performance of these fibers in other applications due to its relatively high nonlinearity, low damage threshold, and poor transparency at short and long wavelengths. In particular, the ultraviolet (UV) range, which is gaining significant interest today, faces challenges with silica fibers due to Rayleigh scattering, which results in losses exceeding dB/m levels for wavelengths below 300 nm. These fibers also have a low laser damage threshold and are prone to solarization. To address these challenges, hollow-core photonic crystal fibers (HCPCFs), specifically those using the inhibited-coupling mechanism, have emerged as a promising solution [2]. We recently demonstrated the fabrication of IC-HCPCFs with improved core surface quality to reduce surface scattering and microbending losses, which are the dominant loss mechanisms at these wavelengths. [3]. This achievement was made possible by innovating the traditional HCPCF fabrication process. Our technique involves applying counter-directional gas and glass flows within the fiber microstructure during the drawing process, which adds shear to the glass membranes of the microstructure, resulting in smoother core surfaces. This has led to record-low loss IC-HCPCFs in the short-wavelength range, with values below 50 dB/km in the UV spectrum, and has enabled the first demonstration of high average power delivery at 343 nm [4].

In the present work, new IC-HCPCFs have been fabricated by using this process and optimized to guide light at another specific industrial wavelength of interest, i.e. 266 nm. A patchcord has then been assembled and characterized to demonstrate its

capability to deliver such UV laser beam while meeting industrial requirements

Experimental results

The cross-section of the fiber used in this work is shown in Fig. 1a. It represents a single-ring tubular lattice IC-HCPCF whose microstructure encompasses a set of eight tubes with a silica thickness of 300 nm and a diameter of 11 μm . This lattice surrounds the hollow core, which has a diameter of approximately 29.5 μm , while the fiber's outer diameter measures 200 μm without any coating. The fiber was fabricated using the standard stack-and-draw process, combined with our new "shear" technique to reduce the silica roughness at the core/cladding interface. This method, as previously described, significantly improved the core surface quality by a factor of three, enabling lower transmission losses in the deep ultraviolet (DUV) range. Fig. 1b shows the transmission spectrum of a 2 m long piece of the fabricated fiber and Fig. 1c the losses obtained by using a laser-driven plasma source (ENERGETIQEQ-99X-FC) and an optical spectrum analyzer (Ocean Optics HR4000CG-UV-NIR) during a cutback measurement. The losses in the UV spectral range are found below 100 dB/km over 30 nm with one minimum of 35 dB/km at the industrial wavelength of interest 266 nm.

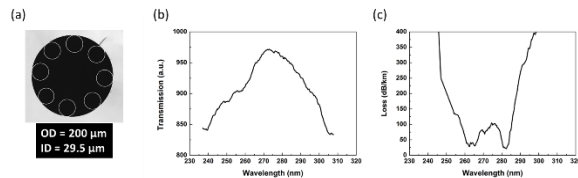


Figure 1: (a) Cross-section of the fabricated IC-HCPCF, (b) transmission and (c) loss curves measured in DUV range.

The 2-meter piece of IC-HCPCF was then used to fabricate a beam delivery patchcord. At both ends, the HCPCF was carefully prepared and mounted with SMA905 connectors without inducing extra-losses (see Fig 2a). The entire assembly is encased in a steel helix to protect the fiber against mechanical stress and optical dysfunctions. In order to investigate the performances, a UV laser beam developed by Crylas laser has been injected into our patchcord. The system operates at 266 nm in nanosecond regime (pulse duration of 1 ns) with a maximum average power of 50 mW and an energy of

50 μJ for a repetition rate of 1 kHz. In the set-up, half waveplate and a PBS have been added to control the power at the patchcord input and a set of mirrors and a lens to optimize the mode matching. The total insertion losses from these optics, including the beam shaping to match the fiber's mode, were measured at 2.3 dB. At the output of the patchcord, a camera has been used to control the near and the far fields which confirms the excellent mode quality found near to the fundamental mode LP_{01} as shown by the Fig. 2b. The output transmitted power was also measured by a power meter resulting to a maximum of 93% transmission efficiency for the optimum coupling conditions. The stability of the UV delivery was finally studied by making an endurance run at the maximum average power which corresponds to 27 mW launched into the patchcord. The transmitted light was monitored over 680 hrs and plotted in Fig 2c. The power fluctuations show a relative RMS of less than 2.6% with no degradation observed on the fiber over this timescale.

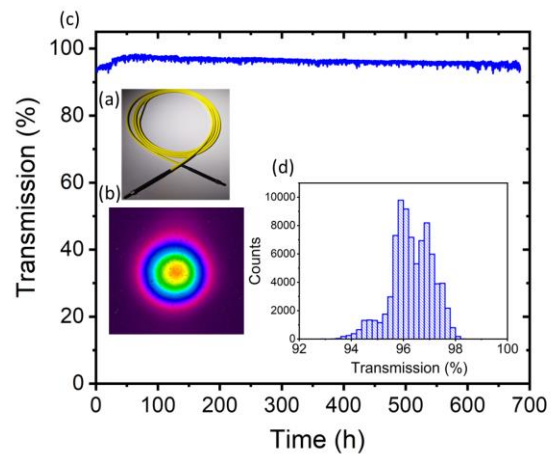


Figure 2: (a) Assembly SMA905 2m-long patchcord, (b) far field measured at the output of the patchcord (c) transmission over 680 hrs and (d) standard transmission fluctuation measured during the endurance.

Conclusion

In conclusion, following the recent development of a new generation of hollow-core photonic crystal fibers (HCPCF) with reduced surface roughness, a 266 nm beam delivery patchcord has been successfully fabricated and tested. The system demonstrated a UV transmission efficiency of 93% over 680 hours, with no observed degradation in the fiber. These results highlight the significant potential of HCPCF for UV light transmission, which can be advantageous in various applications, including the medical field and

enhancing photolithography processes. Additionally, gas-filled versions of these hollow-core fibers are currently being investigated for integration into frequency conversion systems developed by Glophotonics [5].

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