High Power 2053 nm Transmission through Single-mode Chalcogenide Fiber

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Abstract: An in-house drawn chalcogenide fiber sustained 12.2 MW/cm^2 CW irradiation on the facet without damage, limited by available laser power. After depositing single-layer, anti-reflection coatings on the fiber facets, 90.6% transmission was achieved with 10.2 W output.
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1. Introduction

In order to transmit light beyond silica's ~2.4 µm edge, it is necessary to use different glass compositions. Commonly used IR glasses are heavy-metal oxides (such as tellurite and germanate glasses), halides (fluorides such as ZBLAN), and chalcogenides (ChGs) [1]. While ChG fibers allow one of the broadest mid-infrared (MIR) transmission windows from 1.5 – 10 µm, their mechanical robustness is generally considered unsatisfactory. By employing a multimaterial, hybrid fiber-fabrication process, low-loss and robust ChG fibers have been drawn in-house. We have recently reported on their factor of 1000 improvement in tensile-strength as well as optical losses ≤ 1 dB/m [2].

For many applications, such as remote sensing and medicine, fiber delivery of high power mid-IR light is valuable. Previous CW demonstrations have transmitted 226 W at 5.4 µm through a 1 mm diameter multimode ChG fiber [3]. For single-mode delivery, 2.1 W was transmitted at 2 µm limited by fiber failure at ~5 MW/cm^2 input intensities [4]. In this manuscript, high optical power handling is investigated with in-house drawn ChG fibers. A >15 W, 2053 nm, CW fiber laser system is utilized for this task. Over 10.2 W is propagated through the fiber with 90.6 % transmission after depositing anti-reflection (AR) coatings on the fiber facets. The intensity on the input facet is estimated to be 12.2 MW/cm^2 without failure.

2. The chalcogenide fiber under test

The ChG fiber core composition is $As_{39}S_{61}$ and the cladding is $As_{38.5}S_{61.5}$, giving a numerical aperture (NA) of 0.2. The outer polymer jacket is PEI (polyetherimide). The approximate fiber dimensions are 12.3/140/700 µm diameter for the core/cladding/polymer. The large outer polymer jacket is what enables the robust mechanical properties. Three 20 cm long sections were tested, all with polished facets. Figure 1(a) is an optical image of a bare polished facet, with an inset showing the core and cladding. One of the fibers was placed in an electron beam evaporator (Temescal FC-2000) which deposited a 305 ± 10 nm single-layer of Al_2O_3 to form an AR coating on both facets. Figure 1(b) shows an optical image of the coated facet. While it is not distinguishable in Figure 1(b), the coating had minor cracks throughout the outer polymer, but none in the glass region. This is likely due to differences in the coefficient of thermal expansion. Changes in deposition rate or material choice will improve the coating quality.

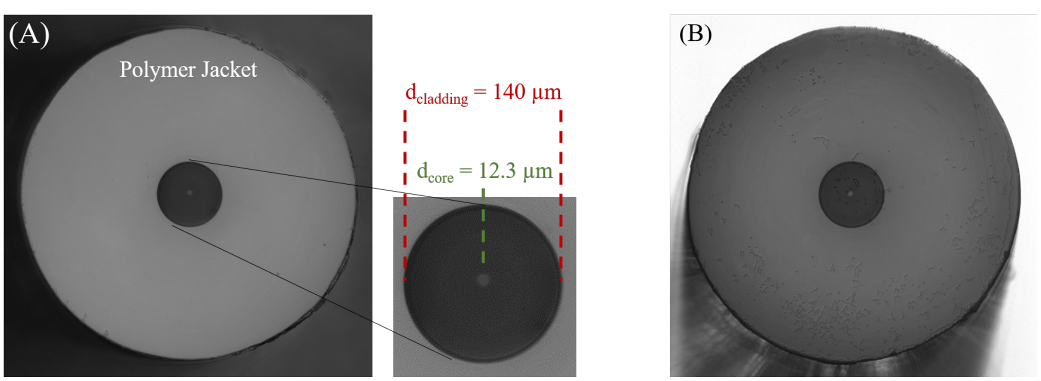

Fig. 1. (a) Optical image of polished chalcogenide fiber facet, inset shows enlarged image of glass region. (b) AR coated fiber facet.

3. Laser transmission setup

The laser used is a diode seeded, single-mode, thulium-doped fiber amplifier with 15 W CW maximum output power. The spectral linewidth is less than 1 MHz, with a spectral signal-to-noise ratio >60 dB. The output is also polarized with a polarization extinction ratio >16 dB. As shown in Figure 2, the laser output is first sent through an isolator. This is critical to prevent optical feedback from the ~17% Fresnel reflection off the uncoated ChG facet. Next, a light valve allows the incident power to be controlled via a half-wave plate (HWP). A wedge samples a portion of the beam for real-time calibration of transmitted power. For the ChG fibers tested, a 1-to-1 imaging system is used consisting of two 11 mm focal length molded aspheric lenses (Thorlabs A397TM-C). The theoretical coupling efficiency, using Zemax®, should exceed 99%. The output imaging lens has a 0.5 NA to capture residual cladding light.

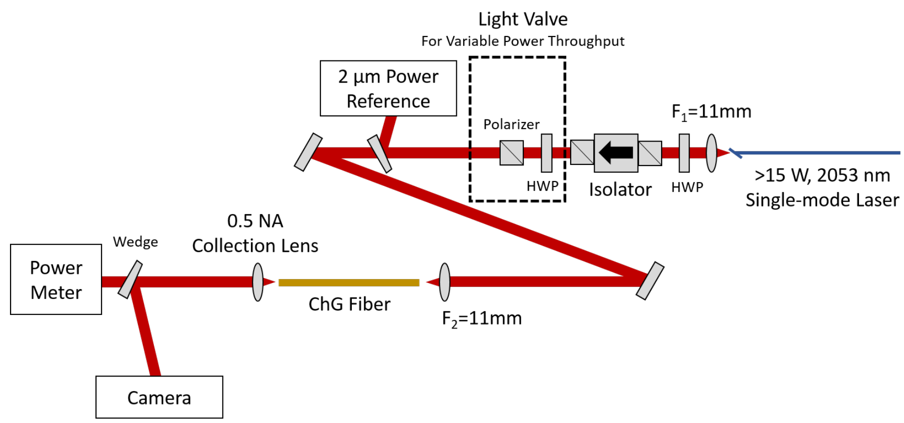

Fig. 2. Experimental setup for high power transmission tests of the ChG fibers. The 2 µm power reference meter and output power meter are synchronized for real-time data acquisition.

4. Results and Discussion

After accounting for losses through the free-space elements, the maximum power incident on the fiber facet was ~12 W. Figure 3 shows the transmission results for two uncoated fibers and one coated fiber. Due to Fresnel reflections, the maximum attainable transmission is ~69% for an uncoated ChG fiber. Assuming 100% coupling efficiency, the 65.5% measured transmission corresponds to a maximum propagation loss of ~1.0 dB/m (in agreement with previous demonstrations [2]). The AR coated fiber enabled >90% overall transmission with a maximum output power of 10.2 W. Assuming 100% coupling efficiency and ~1.0 dB/m propagation loss, this indicates that the AR coatings are each operating with >97% transmission. The maximum intensity estimated on the facet was 12.2 MW/cm^2 for the uncoated fiber and 11.1 MW/cm^2 for the coated fiber (differences are due to laser output power at time of measurement). No damage was observed during the tests, with further power scaling limited by the laser.

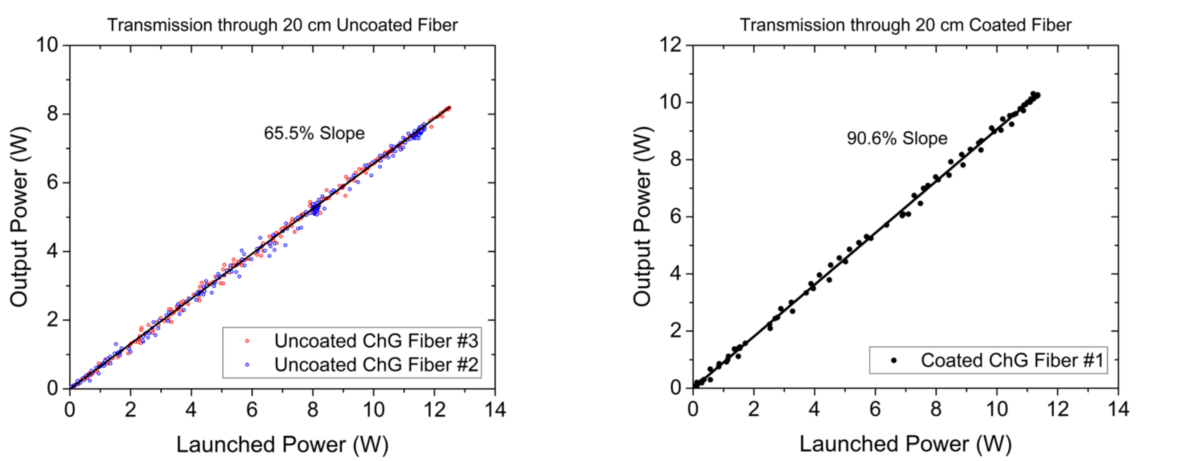

Fig. 3. Left: Transmission measurements for 20 cm long, uncoated, chalcogenide fibers at 2053 nm. Right: Same measurements with an AR-coated fiber, which enabled >90% transmission.

The output beam profile at maximum power through the coated ChG contained upwards of 20-30% of the laser power in the glass cladding. This is due to thermal lensing occurring in the molded aspheric lenses (Thorlabs A397TM-C). The beam profiles exiting the ChG fiber are shown on the left side of Figure 4 for varying power levels *incident on the collimating lens* F_1, while the power incident on the coupling lens F_2 was maintained at 0.5 W using the variable attenuation of the light valve. The plot on the right side of Figure 4 shows that when increasing the optical load on lens F_1, cladding light increases due to coupling degradation via thermal lensing. It is expected that cladding light will remain <5% at high powers when using the appropriate lenses. Investigations utilizing a FLIR infrared camera are also planned to monitor scattering defects and thermal signatures in the ChG fiber [5].

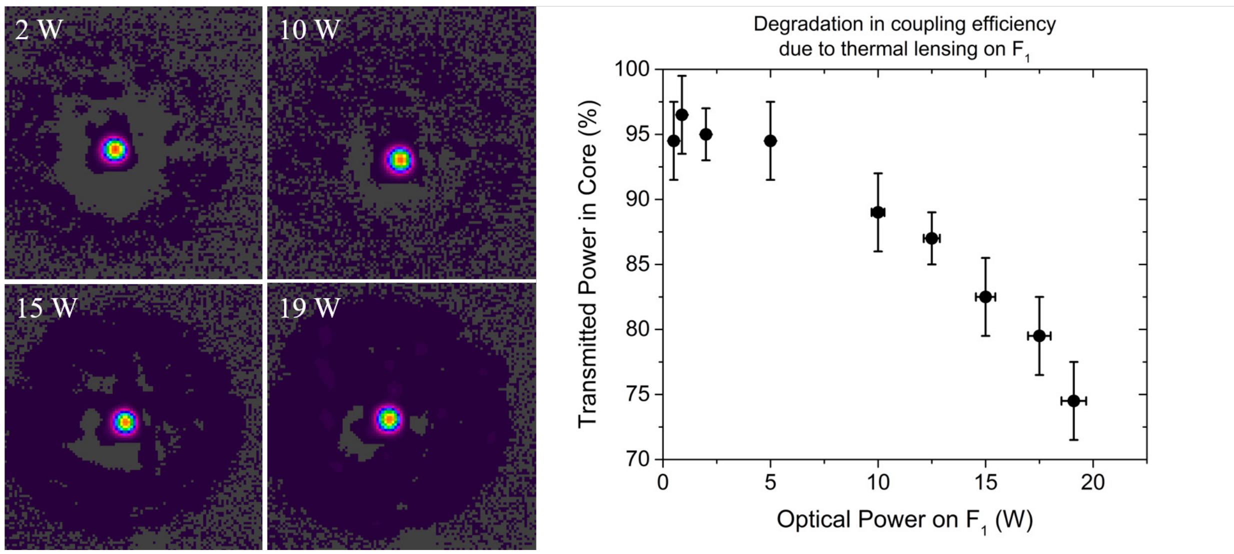

Fig. 4. **Left:** Transmitted beam profiles while increasing the optical load on F_1 (collimating lens) from 2 W to 19 W. **Right:** Measured power in the fundamental mode relative to cladding while increasing the optical load on F_1. The degradation in coupling efficiency is due to thermal lensing in the molded aspheric lenses (Thorlabs A397TM-C).

5. Conclusion

High power (>10 W) transmission at 2053 nm is investigated on an in-house fabricated single-mode chalcogenide fiber reinforced with a polymer jacket. Input power densities of 12.2 MW/cm^2 are reached without damage. AR-coating the fiber enables 90.6% overall transmission with 10.2 W through the fiber. The output beam profile is single-mode, however thermal lensing in the molded aspheric lenses causes degradation in the coupling at high powers. Ongoing investigations utilizing a FLIR infrared detector will monitor the thermal signatures and any scattering defects.

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