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Polishing, Surface Quality, and Coatings for High Power Fibers

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Precision Photonics Corporation, in conjunction with Nufern, is developing high damage threshold, low absorption Anti-Reflection (AR) coatings for high power fiber lasers.

A standard practice for reducing optical damage at fiber end faces is to use a fused 'coreless' endcap that allows the beam to diverge before reaching the glass/air interface, greatly reducing the irradiance or fluence at that surface (Figure 1). An additional requirement for such endcaps is to minimize any back-reflection into the fiber laser or fiber amplifier – both into the core and into the cladding. The simplest way to accomplish this is to use an uncoated angled-face endcap, similar to an angled fiber tip, and in this case back-reflections can be reduced 40dB into the fiber core [1]. The disadvantages of an uncoated angled-face endcap are (1) beam steering occurs, complicating the optical layout, (2) tight angular tolerances must be maintained on the end face, (3) a rotational tolerance also applies with polarization-maintaining fiber, (4) sufficient surface quality must still be achieved on that end face to reduce back-reflection and damage, (5) approximately 4% of the output light is lost due to Fresnel reflection, and (6) much of the reflected light is coupled into the cladding and must be dealt with as heat. Points (5) and (6) become more problematic at high powers, driving the need for a better solution. A potential improvement to angled-face endcaps for reducing the back-reflection is to use an AR coating. It may be that both an angled-face and an AR-coating are advantageous. An AR coated endcap includes additional processing steps, and additional risk from failure of the coating, so there is a need for improved AR coatings with high CW laser damage threshold, extreme durability, and outstanding reliability.

Ion Beam Sputtering (IBS) deposition process is the standard for low-loss, low-absorption coatings capable of handling extremely high irradiances and fluence, and is discussed first. For fiber laser applications, a high quality end face is critical to achieving low back-reflection and a high laser damage threshold. The surface quality for cleaved, commercially-polished, precision-polished, and laser cleaved fibers is discussed next. Surface finish is compared to that for high damage threshold free space optics, as a reference. AR coatings deposited using IBS, for several relevant configurations, will be presented, including results from photothermal absorption testing. AR-coated fiber endcaps have also been tested using a Nufern fiber laser up to 1kW, and results will be presented.

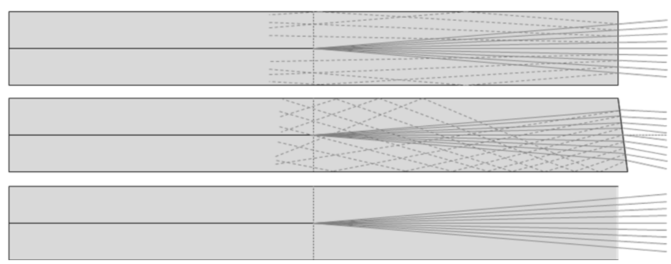

Figure 1. (top) Coreless fiber endcap fused to large mode area fiber, with the dashed lines showing back-reflected power. (middle) Same, with an angled end face on the endcap. (bottom) Same, but with an AR-coated end face on the endcap.

ION BEAM SPUTTERED COATINGS

Fiber endcap AR coatings must have low absorption and a high laser damage threshold, which for CW laser applications requires the use of very low loss coating materials. Ion Beam Sputtered (IBS) coatings offer low scatter and absorption losses, superior durability and environmental stability compared to conventional or ion-assisted evaporated coatings. This makes them ideal for high fluence solid state applications which face extreme temperatures or other environmental factors that can affect optical or mechanical performance [3]. While notable research has been done with IBS coatings in recent years, much of this

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work has been focused on pulsed applications [4,5]. With ever-increasing thermal loads and irradiances seen in current CW solid state lasers, this work represents a step towards a better understanding and optimization of CW power handling capability. The CW laser damage threshold is expected to be dominated by thermal effects connected to residual absorption levels of the coatings. Local electromagnetic field levels are much lower in CW applications than for nanosecond pulsed applications. As a result, field-dependent damage mechanisms such as multi-photon absorption and ionization are not expected to be limiting factors to the laser damage levels. Given the demonstrated low absorption levels achieved for IBS coatings, with ~ few ppm bulk absorption [6], this type of coating deposition process is ideal for producing high reliability, low loss coatings for CW applications.

FIBER CLEAVING AND POLISHING

Standard fiber cleaving is well established, and is known to produce surface quality acceptable for a wide variety of applications. This is particularly true for the core region of a cladded fiber. However, when a cleave is applied to a coreless fiber endcap, the small 'chip' that often results from the cleaving process presents an undesirable surface quality defect that can limit final beam quality. Examples of this chip are shown in Figure 2.

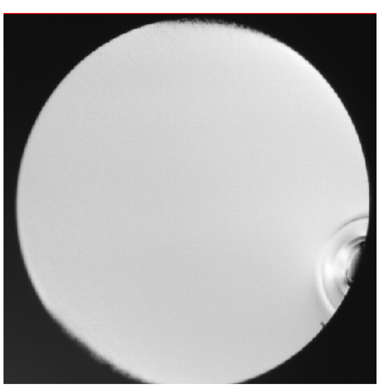

Figure 2. Example of a cleaved fiber endcap showing the typical residual chip from the cleaving process. Elimination of this chip is a delicate process that is not highly reliable.

An alternate cleaving method is the use of newer laser cleaving instruments. These devices typically use a CO2 laser acting as an optical blade that slices through the fused silica fiber or endcap material, which is highly absorbing at ~10μm wavelength. This process is also not ideal and can leave a variety of surface defects, including regions with melt-like appearance as well as insufficient final flatness. An example of this process is shown in Figure 3.

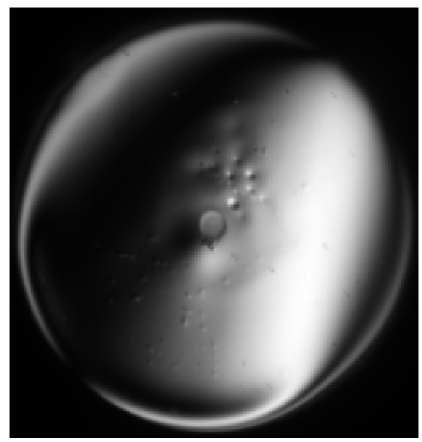

Figure 3. Example of a CO_2 laser-cleaved fiber showing regions with residual surface defects and undesirable surface irregularity.

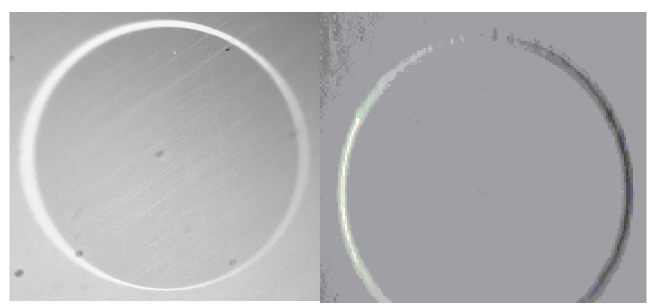

Figure 4. (left) Example of a fiber (in a ferrule) polished using standard fiber polishing techniques, adapted from the telecom industry. The poor surface quality is evident in the form of visible scratches and sleeks. (right) Example of a fiber (in a ferrule) polished by Precision Photonics, using techniques adapted from bulk optics. This process results in a "laser quality" finish, with <10 Angstroms RMS surface micro-roughness and ~λ/50 residual curvature, as measured using a white light interferometer.

Fiber polishing is another method to produce an optical quality surface, but the results vary from ‘barely acceptable for low power’ to a high power laser quality finish. Typically, for polishing, the fibers are first mounted into a ferrule for mechanical rigidity. Results for fiber polishing are shown in Figure 4.

Superior surface finish does not necessarily translate into superior performance in a kW-level CW fiber laser system, however. The performance for each of these situations should be compared under real operational conditions.

COATING AND OPERATIONAL RESULTS

The coatings tested in this work were deposited on 400µm diameter, polished fiber endcaps, 400µm diameter cleaved endcaps, and 400µm diameter angle-cleaved endcaps. All the endcaps were subsequently cleaned using de-ionized water, acetone and isopropanol, and ultrasonics. AR coatings were deposited using an automated IBS coating chamber. Operational results for the fiber coatings are shown in Figure 5, and we expect to be able to discuss additional results in the near future.

The absorption for the coating in Figure 6, as measured via the witness sample from the coating run, is 3.6ppm. This value was measured using photothermal absorption [7], which provides a sensitive, non-destructive means for evaluation of coatings. Based on results with comparable coatings, we believe this absorption can be reduced further. Detailed tests are underway to separate the causes of this absorption at the single-digit ppm level, including: (1) residual effects from the bulk material, (2) residual effects from the polish or cleave, (3) cleaning procedure, (4) contamination during coating from other materials associated with the fiber assembly, and (5) minimization of the absorption in the coating.

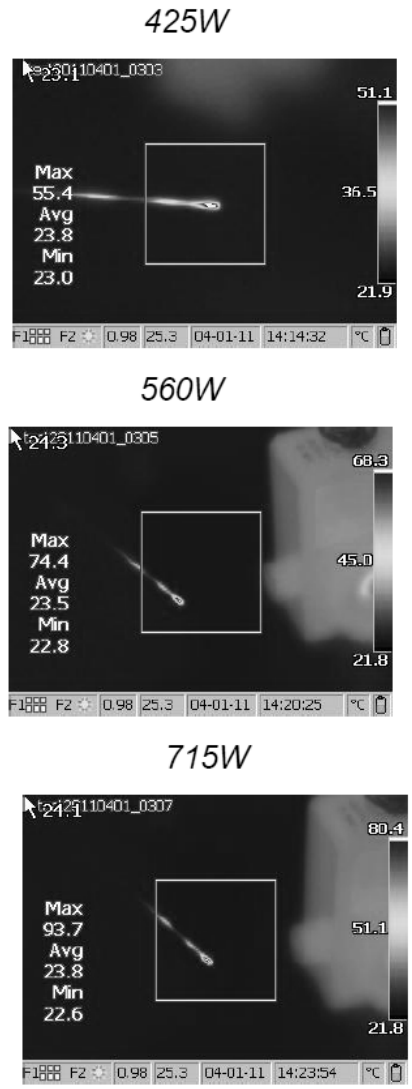

Figure 5. Thermal images of an AR coated, 4° angle-cleaved fiber endcap under operational conditions of 425W, 560W, and 715W. The CW fiber laser/amplifier system is operated at 1064nm. At 715W, the temperature of the fiber tip is ~100°C.

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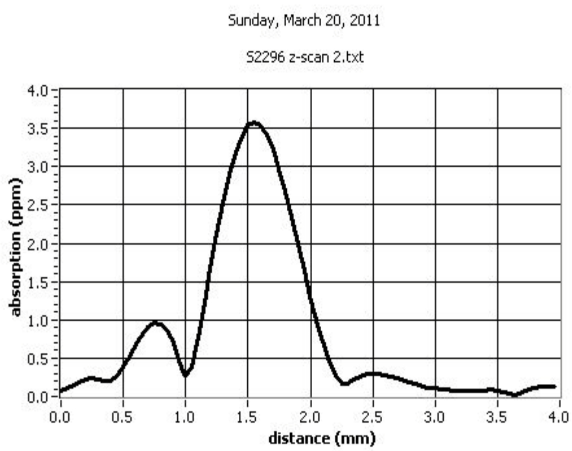

Figure 6. Absorption measurement for the witness sample from the fiber end-face AR coating run. The value for the coated surface is 3.6ppm.

CONCLUSIONS AND NEXT STEPS

Many lessons have been learned during this development, including:

- Cleanliness for the fiber surfaces is crucial, and more can still be learned
- Contamination of the fiber end face must be carefully controlled
- The required surface polish for CW operation beyond 1kW is still undetermined. Cleaves are known to work, and polished end faces are known to work. It is not clear if an improved polish leads to improved power output or improved reliability
- Adhesion of the IBS fiber coatings is excellent

One promising next step for this effort is to extend these results to the 2μm region for use with the new generation of high-power Tm-doped fiber lasers. Low absorption coatings in that spectral region have recently been verified [8].

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