High power cladding light strippers

Alexandre Wetter, Mathieu Faucher, Benoit Sévigny
ITF Laboratories, 400 Montpellier, Montreal, Québec, H4N 2G7, Canada;

ABSTRACT

The ability to strip cladding light from double clad fiber (DCF) fibers is required for many different reasons, one example is to strip unwanted cladding light in fiber lasers and amplifiers. When removing residual pump light for example, this light is characterized by a large numerical aperture distribution and can reach power levels into the hundreds of watts. By locally changing the numerical aperture (N.A.) of the light to be stripped, it is possible to achieve significant attenuation even for the low N.A. rays such as escaped core modes in the same device. In order to test the power-handling capability of this device, one hundred watts of pump and signal light is launched from a tapered fused-bundle (TFB) 6+1x1 combiner into a high power-cladding stripper. In this case, the fiber used in the cladding stripper and the output fiber of the TFB was a 20/400 0.06/0.46 N.A. double clad fiber. Attenuation of over 20dB in the cladding was measured without signal loss. By spreading out the heat load generated by the unwanted light that is stripped, the package remained safely below the maximum operating temperature internally and externally. This is achieved by uniformly stripping the energy along the length of the fiber within the stripper. Different adhesive and heat sinking techniques are used to achieve this uniform removal of the light. This suggests that these cladding strippers can be used to strip hundreds of watts of light in high power fiber lasers and amplifiers.

Keywords: High power, tapered fused bundle, packaging, cladding strippers, fiber laser, optical engines, double clad fiber

1. INTRODUCTION

Fiber lasers and amplifiers are used in a growing number of applications. They have received great attention because of their ability to provide high wall-plug efficiency and excellent beam quality even at high power levels [1-4]. As fiber lasers mature towards commercial deployment, an intense focus on their reliability and that of their components is required. With the current progress in this field, reliability demonstrations are made at increasingly higher power levels. Output powers in the multi-kilowatt range have been reported, using either discrete bulk components [5,6], or all fiber components such as tapered fused bundle (TFB) [7,8] for coupling in and out of the fiber gain medium.

In order to increase the robustness of all-fiber lasers and amplifiers at high power, it is important to properly manage unwanted light. In addition, by dealing with this unwanted light, it is possible to improve the quality of the system and the output beam. This unwanted light is generated all along the chain of components that make up a system, each component is designed to perform a specific task; for example, tapered fused bundle (TFB) couplers are well suited to combine signal and pump light and are characterized by intrinsically low transmission loss, however, this component needs to be protected from backward travelling light in order to safely perform at high power in a real system. The most meaningful benchmark, when considering the power handling of pump stripper, is the capability of the device to dissipate cladding light and not disturb the transmitted signal flowing through the core.

In this work, the characterization of the light that can be stripped and its impact on package temperature rise in high power operating conditions is studied and demonstrated.

This paper is structured as follows: In section 2 a brief description of the different sources of unwanted light is given and the advantage of using pump strippers is explained. In section 3, we will present the methodology used to design high power pump strippers using mathematical models and experimental results, finally, in section 4 we discuss the performance of these pump strippers in a high power application.

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2. SOURCES OF UNWANTED CLADDING LIGHT AND FUNCTION OF PUMP STRIPPERS

Both all-fiber lasers and amplifiers are currently composed of assemblies of individual components spliced together, as shown in figure 1, a typical laser/amplifier is composed of a tapered fused bundle (TFB) pump & signal combiner to launch pump into the cladding and signal into the core (for an amplifier) of a double clad gain fiber; for a laser configuration, high reflector and output coupler (low reflector) fiber Bragg Gratings are spliced on. In a perfect system, all signal light is amplified and is constrained to the core, and the pump light is all absorbed by the gain fiber. In reality, there are many sources of loss along the chain of components and leakage of light from one area to another that are qualified here as unwanted light. Fresnel reflection of the output fiber can also re-inject signal light back into the core and cladding of the output fiber.

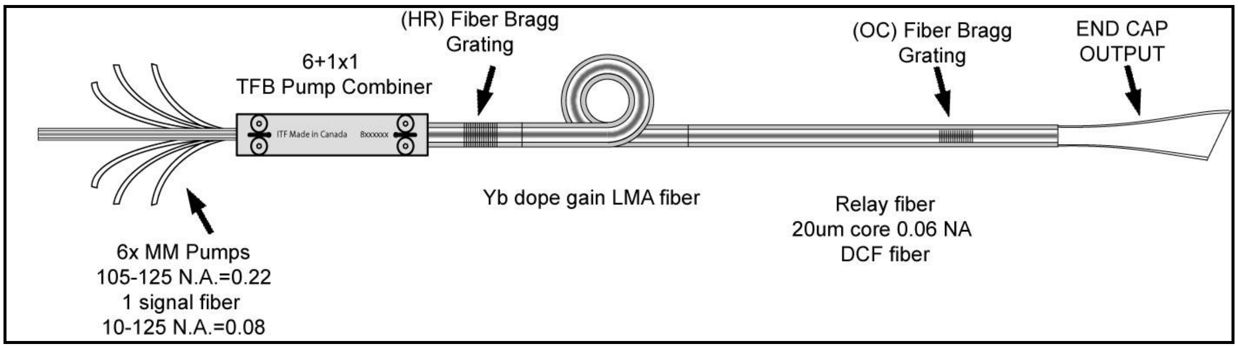

Figure 1 Example of simple fiber laser/amplifier design. An all-fiber 6+1x1 TFB is spliced to a 20-400 Yb doped DCF gain fiber. The Bragg grating acts as high reflector (HR) and output couplers (OC) for a laser configuration. An all-fiber end cap at the output allows beam expansion for safe beam delivery.

The main sources of unwanted light traveling in the cladding can be separated into 3 categories: amplified spontaneous emission (ASE), residual pump light at the end of the gain fiber and core light leaking into the cladding or being reflected into the cladding. All of these generators of unwanted light are spread along the chain of components.

ASE is naturally generated by the excited gain medium. It can account for several watts of the total unwanted light in a high-power laser system, more in an amplifier configuration.

Residual pump consists of the remaining pump light after the gain fiber. Note that this light is mode scrambled and selectively absorbed since attenuation in the gain fiber is a function of N.A. Residual pump light can reach 100W or more in kW class systems.

Many different splices are present in the optical path of an assembly. Some are simple and link identical fibers together, others are more complicated as shown in figures 2a and 2b. In order to prevent loss of signal or beam quality, the mode field diameter (MFD) of each fiber must be matched before the splicing, in both cases, the splice will produce some core loss due to scattering and some core light will be launched in the cladding. In the case of a double-clad fiber (DCF), this light will be guided in the cladding and can interfere with the core light until it is eventually stripped.

At the output of the assembly, the light will travel either through a passive fiber, an active fiber or a beam expanding end-cap, all of these terminations can be straight or angled however the final fresnel reflection will be coupled light back into the assembly or DCF fiber.

Most of the unwanted cladding light generated by the above sources can be dealt with by a pump stripper. Introduced at the right place in the chain of components, pump strippers will absorb an important part of the unwanted light in the cladding without perturbing the signal. By spreading out the heat load generated by the unwanted light that is stripped, the package will remain safely cool, rather than have other areas of the system overheat. In figure 3, a stripper is introduced in an all-fiber laser assembly.

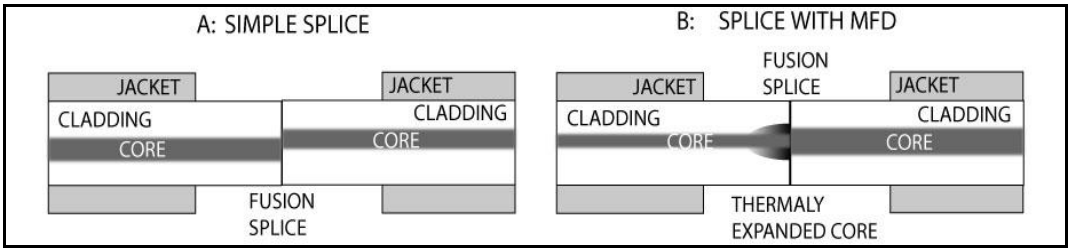

Figure 2 Two examples of splice loss leading to leakage of core light into the cladding. Figure A illustrates a simple splice of 2 identical fibers where the cores are misaligned. Figure B illustrates 2 fibers having different core diameters between which occurs a mismatch of MFD's between the 2 cores.

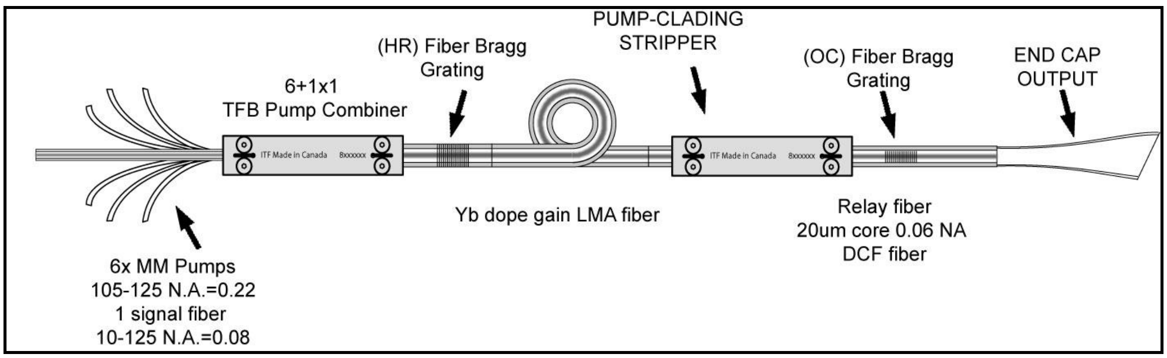

Figure 3 Example of simple fiber laser/amplifier design. An all-fiber 6+1x1 TFB is spliced to a 20-400 Yb doped DCF gain fiber. The 2 Bragg gratings act as high reflector (HR) and output couplers (OC). An all-fiber end cap at the output allows beam expansion for safe beam delivery. A pump/cladding stripper is introduced after the gain fiber to strip all the unwanted light in the forward and backward direction

3. DESIGNING A HIGH POWER PUMP STRIPPER

The obvious thing to do when attempting to strip cladding light in a DCF fiber is to recoat the DCF fiber with a high index coating. This polymer recoat will couple the light out of the cladding, the magnitude of the stripping will be a function of the difference in index between the fiber's cladding and the recoat, the NA of the light traveling in the fiber and the outer diameter of the fiber.

In order to evaluate the performance of this device, pump and signal light is launched in a tapered fused-bundle (TFB) 6+1x1 combiner to which a high power cladding stripper is directly attached at the output. In this case, a simple 20/400 μm 0.06/0.46 N.A. dual core fiber was spliced to our TFB, the original fluoroacrylate jacket was removed over 5cm. The exposed fiber was recoated with a high index polymer and embedded in a high power package in order to appropriately heat sink the polymer. We performed measurements for different lengths of recoat along the axis of the fiber. As shown in figure 4a, we obtained 17dB of attenuation in the cladding by recoating the fiber along 5cm with high index polymer. The far-fields measurements of the emergent light at different lengths of recoat is shown in figure 4b. As shown, cladding borne low N.A. light will not be stripped within the reasonable length of 5cm. This suggests that low NA light leaking from the core (due to coiling for example), would not be stripped. So, by using a high index polymer recoat, the component would not strip low N.A. light and would not attenuate sufficiently.

Furthermore, we measured the temperature rise of the polymer recoat embedded in a high power package. In order to accurately measure the inner temperature, the device was instrumented to provide a temperature-mapping capability inside the fully enclosed package. A capillary tube transecting the adhesive bond in the longitudinal axis was introduced to allow high reflectivity Bragg gratings to be positioned for temperature profiling. Braggs had previously been used for temperature assessment under high power illumination, where thermocouples suffer from large absorption of the optical field [12]. Good correlation between IR camera imaging and Bragg temperature reading as previously been demonstrated [11].

In figure 5, the temperature mapping shows that much of the light is stripped out of the cladding within the first few millimeters. As previously mentioned, the rate at which the light is stripped is function of the difference in index between the fiber's cladding and the recoat, the NA of the light traveling in the fiber and the outer diameter of the fiber. The higher the NA, shorter the distance needed to strip. Since most of the light is characterized by high N.A., a large part of the attenuation will occur within a few millimeters.

The match between the fitted theoretical profile and the temperature reading from the Bragg is also shown. The flared out tails of the distribution are due partly to a measurement artifact created by the presence of the capillaries, there is also convection present at each end of the bond, whereas the model considers this point to be at ambient heatsink temperature.

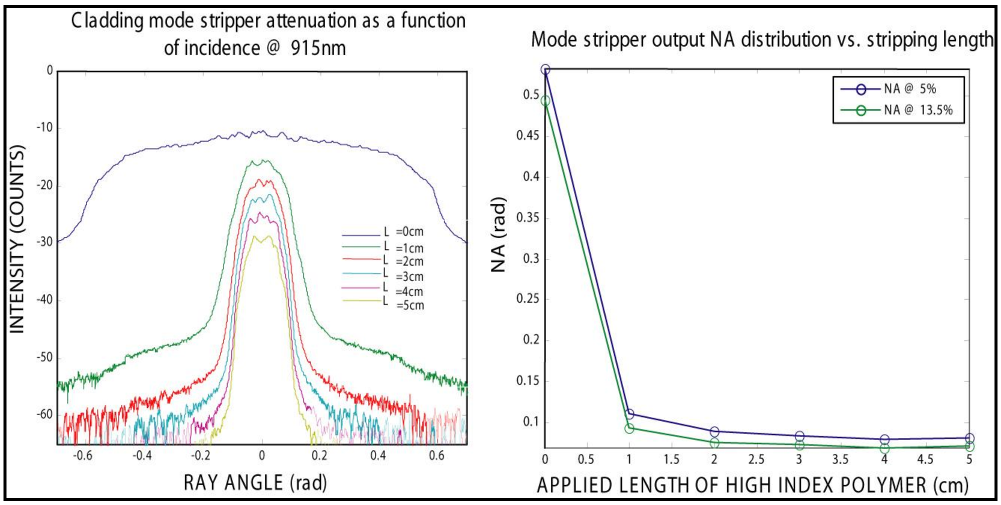

Figure 4 Attenuation and far-field measurements of a pump stripper while stripping cladding light from a DCF fiber using only a recoat of high index polymer

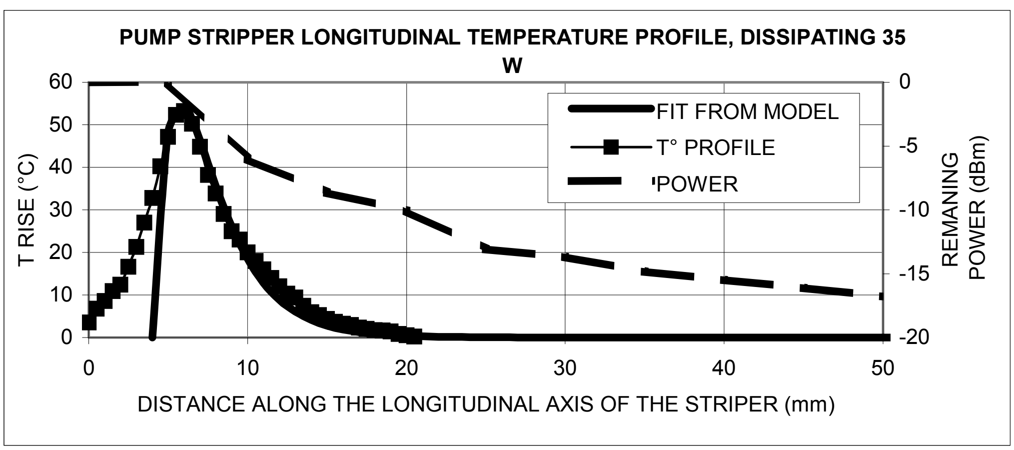

Figure 5 Temperature mapping of a pump stripper while stripping cladding light from a DCF fiber using only a recoat of high index polymer

In order to attenuate the design goal of up to 20 dB of cladding light characterized by a large far field distribution and dissipate 100 watts, two design changes to the above pump/cladding stripper are introduced; Firstly, we locally increase the numerical aperture (N.A.) of the light to be stripped, by increasing the low N.A. light, this will allow the stripper to achieve significant attenuation within a reasonable length. Secondly, stripping the power uniformly over the length of the package and understanding the thermal loading, will allow for high power application.

To demonstrate the benefit of locally changing the N.A. of the light traveling through the stripper, we reproduce the same experiment as previously described and introduce this local increase the N.A. As shown in figure 6, over 20dB of attenuation is achieved. In addition, the far-field measurements show that all light characterized by lower N.A. is now stripped.

In order to minimize localized heating, caused by stripping too fast, a homogeneous high index polymer cannot be used over the entire length. A polymer which would gradually strip the light would be ideal to uniformly spread the heat load. To strip gradually, the refractive index should increase along the length of the stripper. This coating would strip a fraction of the light per unit length. Figure 7 illustrates the ideal situation where all the cladding light is uniformly stripped along the entire length of the package. Different methods can be used to in order to tend towards this situation such as applying different polymers having with different indexes at different locations.

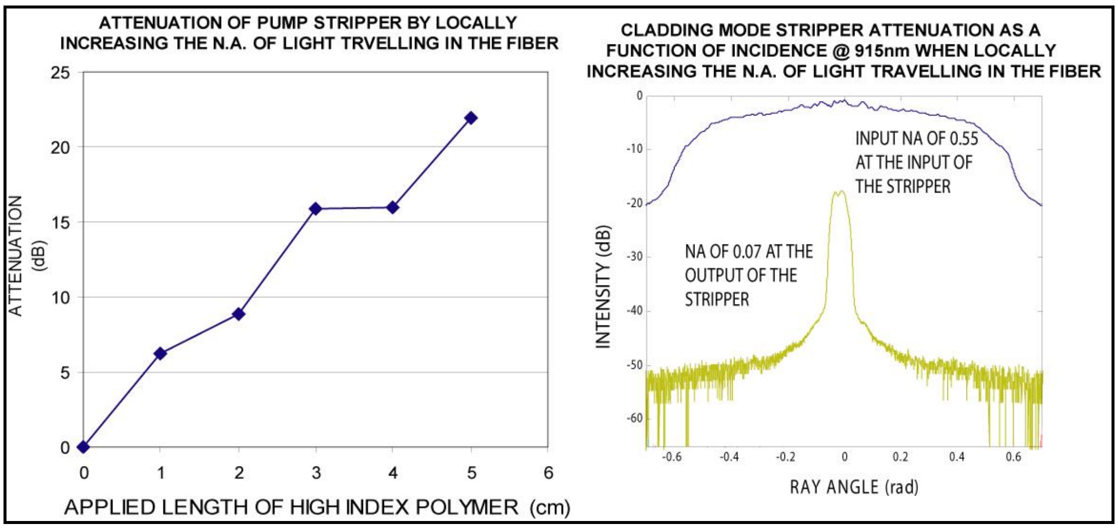

Figure 6 Attenuation obtained by locally increasing the numerical aperture (N.A.) of the light to be stripped within the pump stripper.

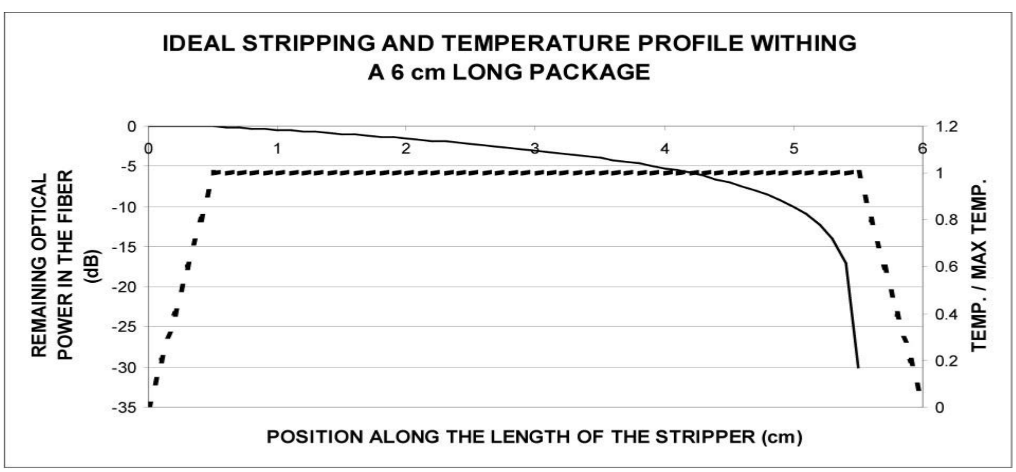

Figure 7 Illustrates the ideal situation where all the cladding light is uniformly stripped along the entire length.

In order to demonstrate that the proposed pump stripper design does not disturb or attenuate the light in the core, we performed the following measurement and observed no loss as seen in figure 8. Mode field adapters (MFA) [7] were spliced at each end of a 20/400 0.06/0.46 fiber to ensure both proper LP01 launch conditions and LP01 filtering at the output. Thus, the observed loss is purely the loss of the LP01 mode through the assembly.

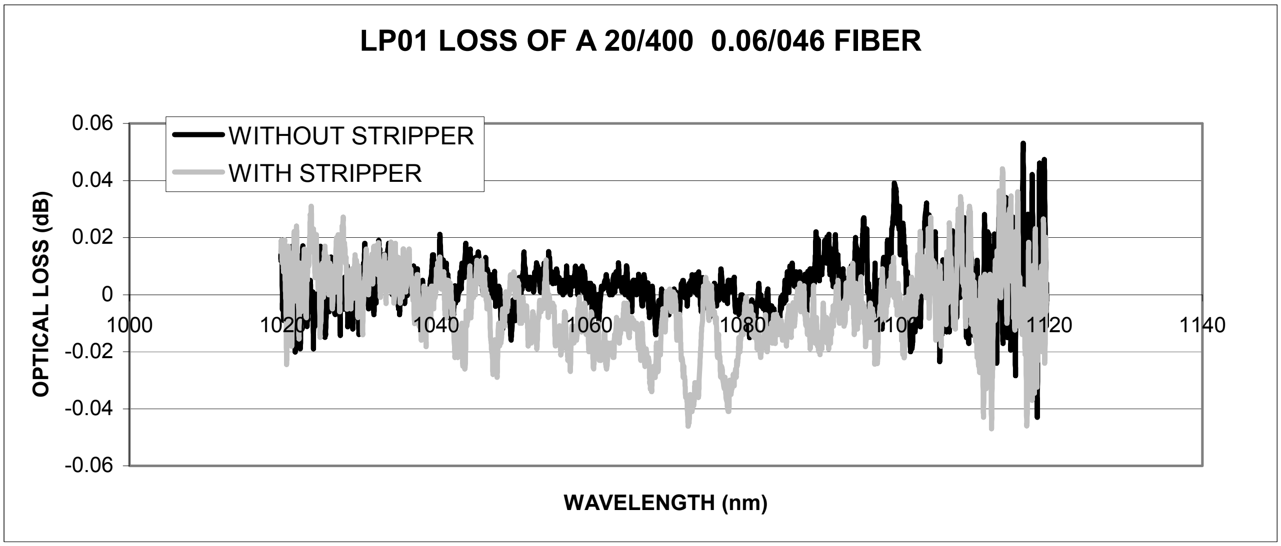

Figure 8 Demonstration that the proposed design for pump-cladding stripping does not induce any core loss. The measure was done by building a pump stripper on a DCF fiber (20/400 0.06/0.46) in between 2 MFA's to ensure both proper LP01 launch conditions and LP01 filtering at the output.

4. PERFORMANCE AND CARACTERISATION IN HIGH POWER APPLICATIONS

By combining the designs discussed above in the same device, we successfully designed, built and tested a device under high power operation. This design has elements that increased the N.A. of the light traveling though the stripper and had 2 different stripping polymers, each having different refractive indeces. Thus, the heat load is separated into 2 regions of the device. The model based on the difference in index between the fiber's cladding and the recoat, the NA of the light traveling in the fiber and the outer diameter of the fiber was used to predict the attenuation of optical power transmitted thought the system. This curve is shown in figure 9 with the experimental measurements of optical power remaining in the fiber while the polymer was applied.

In order to test power-handling capability of this device, over one hundred watts of pump and signal light is launched in a tapered fused-bundle (TFB) 6+1x1 combiner to which a high power-cladding stripper is directly attached at the output. Of this power, 25 watts was signal light which must not be stripped. In this case, the fiber used in the cladding stripper was a 20/400 0.06/0.46 N.A. double clad fiber, which is identical to the output fiber of the exiting TFB. An attenuation of over 30dB in the cladding was measured without loss of signal light. Approximately 78watts of pump light was stripped and absorbed, all the signal light was uninterrupted. The device was actively heat sunk to a water cooled base, instrumented using the same techniques discussed previously in order to measure and map the inner temperature. The inner temperature of the device increased at a rate of 0.4°C/watt dissipated.

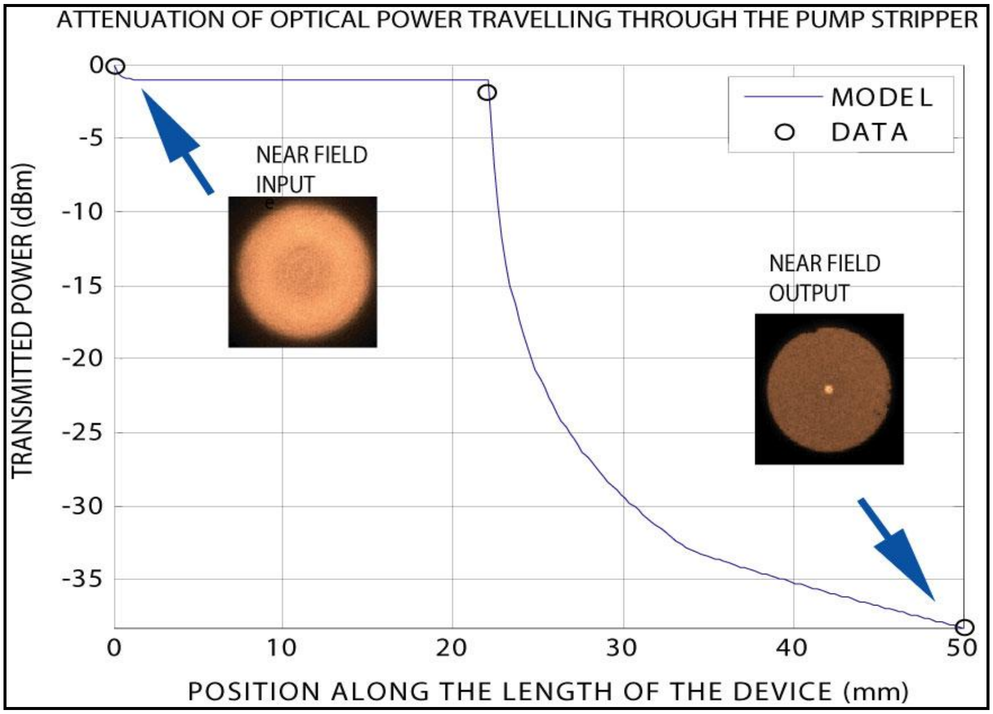

Figure 9 Expected attenuation based on a model which takes into account the difference in index between the fiber and the recoat, the NA of the light traveling in the fiber and the diameter of the fiber. Experimental measurements are also showed.

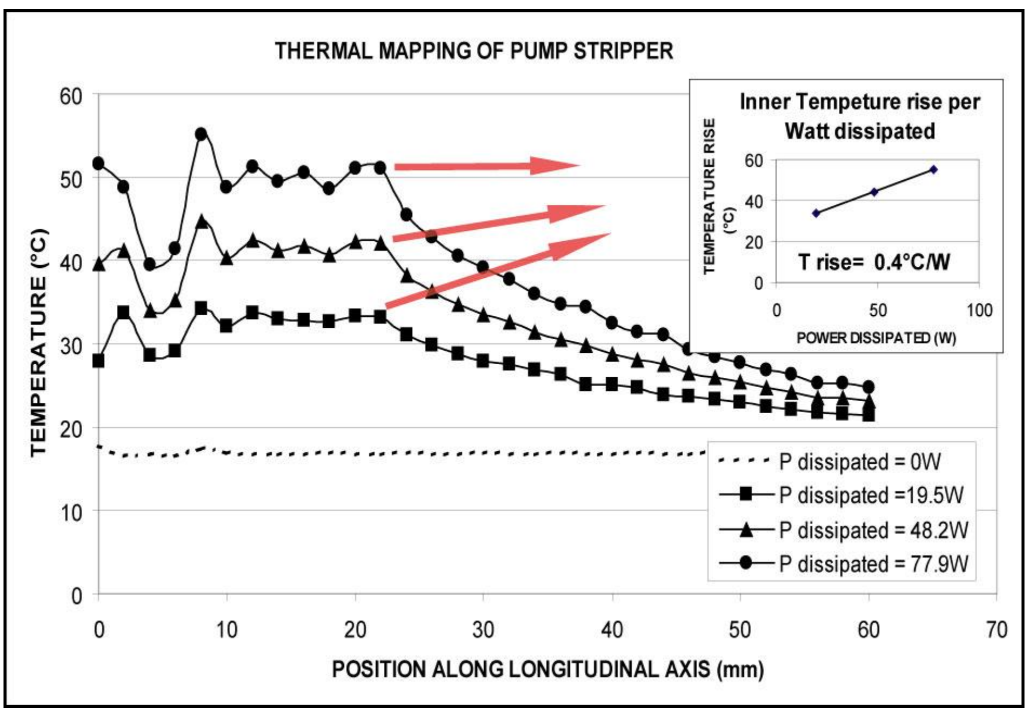

Figure 10 Temperature mapping of a pump stripper while stripping cladding light from a DCF fiber. The stripper used was designed to increase the numerical aperture (N.A.) of the light to be stripped within the pump stripper and strip gradually along the length of the device.

5. CONCLUSION

We began by enumerating the different sources of unwanted light in fiber lasers and amplifiers. We then presented the optical and thermal characterizations of a fiber simply recoated with a high index polymer and exposed the limits of this technique. We then proposed 2 design changes that allow for greater attenuation and which minimize local heating. By combining these 2 designs we demonstrated that stripping 80 watts of pump light with 30 dB of attenuation is possible while not disturbing the signal light. The measured temperature rise suggests that these pump strippers are capable of dissipating over 100 watts of power. Further work needs to be done in order to quantify all these measurements in regard to the diameter of the fiber used in the pump stripper, the thickness of adhesive between the fibers and the package and the type of fiber.

6. REFERENCES

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