High core & cladding isolation termination for high power lasers and amplifiers

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ABSTRACT

As overall power increases in fiber lasers and amplifiers, the amount of optical power which must be dealt with in order to obtain high core to core and core to cladding isolation also increases. This unwanted light can represent hundreds of watts and must be managed adequately. By combining a proper termination (end cap) design and cladding stripping techniques it is possible to obtain a robust output beam delivery component. The cladding stripping techniques are inspired by previous work done on high power cladding strippers. All measurement presented here are done with a flat end cap. Both core to core and core to cladding isolation will be better with an angled end cap. A core-to-core isolation of over 25dB was measured, while core to cladding was over 30dB. Power handling was characterized by the capability of the device to handle optical power loss, rather than transmitted power. The component dissipated over 50 watts of optical power due to isolation. The above results show that understanding the mechanisms of optical loss for forward and backward propagating light in a end cap and the heat load that these losses generate is the key to deliver kilowatts of optical power and protect the integrity of the system.

Keywords: High power, end cap, packaging, cladding strippers, fiber laser, optical engines, termination

1. INTRODUCTION

Fiber lasers and amplifiers are used in a growing number of applications. They have received great attention due to their ability to provide high wall-plug efficiency and excellent beam quality even at high power levels [1-2]. As fiber lasers mature towards commercial deployment, an intense focus on their reliability and that of their components is required. Reliability demonstrations are made at increasingly higher power levels. Output powers in the multi-kilowatt range have been reported, using either discrete bulk components [4,5], or all fiber components such as tapered fused bundle (TFB) [6,7] for coupling in and out of the fiber gain medium.

Both all-fiber lasers and amplifiers are 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, a high reflector and an output coupler (low reflector) fiber Bragg Gratings are inserted in this cavity. Finally, an all-fiber termination is spliced at the output allowing for beam expansion and safe beam delivery.

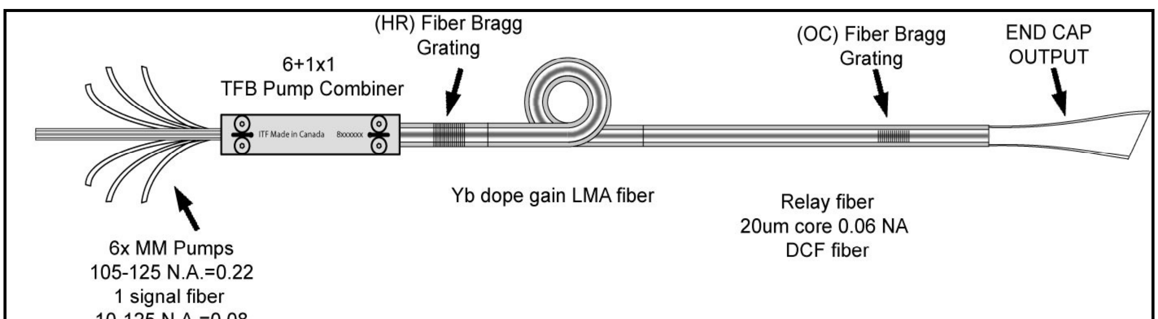


Figure 1. Example of simple fiber laser/amplifier design. An all-fiber 6+1x1 TFB is spliced to a 20-400 Yb doped DCF gain fiber. The Bragg grating acts as high reflector (HR) and output couplers (OC) for a laser configuration. An all-fiber end cap at the output allows beam expansion for safe beam delivery.

Many undesired phenomenons will occur when the optical beam leaves the all glass optical engine. Some of these phenomenon's, such as unwanted back reflections, will lead to stray light amplification that decrease the effective gain in the cavity. Additionally, uncontrolled high peak power pulses of coherent signal light can be re-injected in the cavity and damage the optical engines and there pumps. In order to increase overall reliability of fiber laser and amplifiers, adequate terminations are needed. These terminations (end cap) must provide high core-to-core and core to cladding isolation while ensuring proper beam quality. The core-to-core isolation is provided by the end cap design and the core to cladding isolation is provided by the integrated cladding stripper [3].

In this work, characterization of the signal light exiting the end cap and light being reflected back in towards the all glass optical engine is disused. Temperature rise of the package due to re-injected light in high power operating conditions is studied and demonstrated.

This paper is structured as follows. In section 2, a brief presentation of different end cap designs is given. In section 3, we will discuses the characteristics that high power end cap must provides and present typical performances. Finally in section 4 we will explain how the unwanted light resulting from the high isolation is managed and discuss performances at high power.

2. DIFFERENT END CAP DESIGNS

In figure 2, we illustrate the different areas where core and cladding light travel in a standards end cap design. As core light leaves the output fiber and enters the all glass end cap, the unguided beam diverges without interfering with the sides of the end cap (clipping). At the output face, a portion is reflected back. When traveling back, the angle of the beam increases before re-entering the output fiber. Most of this light will not couple back into the core, since the reflected beam diverges further on the way back to the core.

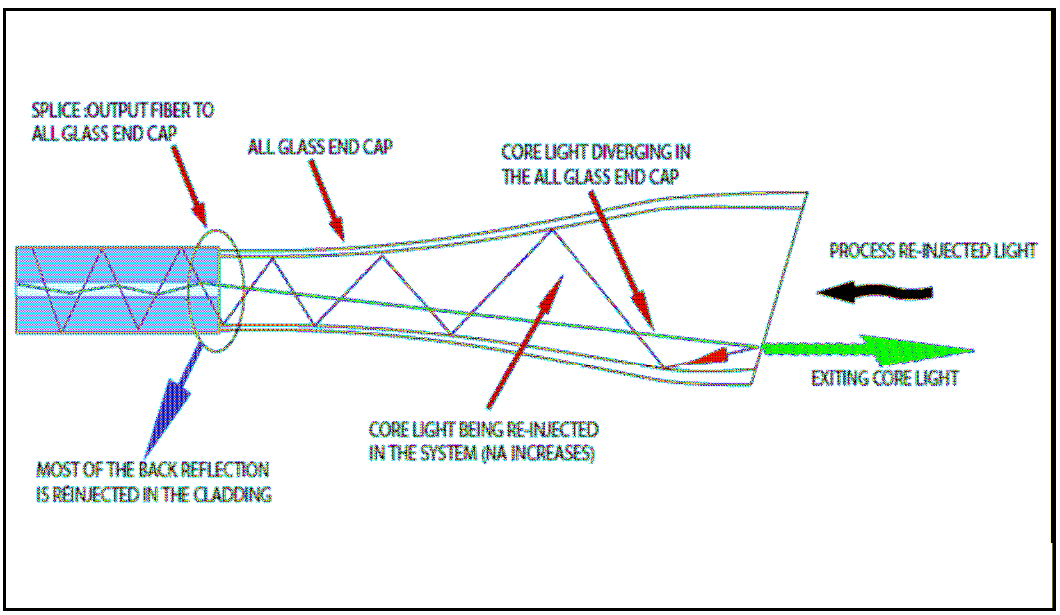


Figure 2 Illustration of a standard end cap design and different areas where core and cladding light travel.

In high power applications, this light, which is not re-injected into the core, needs to be stripped to avoid to be guided into the cladding, and return in the optical engine. This is what we call core to cladding isolation.

In an optical engine (fiber amplifier or laser) the proportion of light that must be managed due to Fresnel reflection depends mainly on two things: the angle at which is polished the end cap and the presence of an anti-reflection coating (AR coating). In the table below, we present 3 different standard end cap designs without any cladding stripping features. For each design we present, the theoretical total back reflection, the portion of this reflected light that will couple back into the core and the complementary portion that will end up in the cladding.

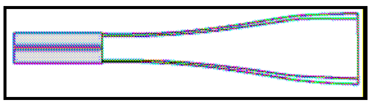
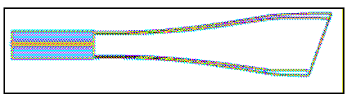
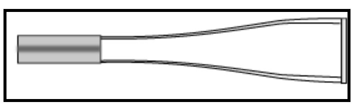
1mm end cap design spliced to a 20/400 0.06/0.46 DCF relay fiber	Core light only, NO integrated cladding stripper		
	Total back reflection	Portion re-injected in the core (core to core isolation **LP01**)	Portion re-injected in the cladding (cladding isolation)
Flat 	4%	37dB	16dB
Angled (EX: 8°) 	4%	~60dB	~20dB
Flat + AR coating 	0.2%	50dB	30dB

Table 1. Three different end cap design are illustrated. Theoretical reflections, core-to core and core-to cladding isolation are given for each design.

In all three designs shown above, the core-to-core isolation is acceptable while the core-to-cladding isolation is poor. In high power application, this cladding light must be stripped and managed properly in order to maintain optimal operation conditions and integrity of the optical engine.

3. IMPORTANT CHARACTERISTICS THAT END CAP MUST PROVIDE

When designing an end cap, the following characteristics must be optimized: 1-Robustness do to high intensity 2- Preservation of beam quality 3-High core to core isolation 4- High core to cladding isolation. By combining a proper end cap design, a cladding stripper and proper packaging techniques, it is possible to achieve interesting result regarding all these important characteristics even in high power applications. As short explanation for each of these characteristics and some examples of the method used to quantify are given.

1-Robustness to high intensity:

As the laser light exits the fiber it travels thru the all glass cylinder (end cap) and starts diverging. When reaching the glass air interface, the density is reduced. This allows to safely deliver the bean without exceeding the damage threshold of the glass (the glass-air damage threshold is 1E9 W/cm2 in CW regime and the bulk damage threshold is 40 J/cm2 @1ns in pulse regime). Figure 3 illustrates two dimensions of 3 dimensional model that is used to optimize the end cap design. The model must take into account core and cladding diameter of the output fiber, numerical aperture and operating wavelength. The length of the end cap, which corresponds to the distance upon which the light diverges, is the calculated length to respect the following guideline: First, the maximum peak intensity for a given mode field diameter must be 10 times smaller then the damage threshold. Secondly, the geometrical shape of the end cap must be design to avoid clipping. Figure 4 shows the air damage threshold limit for CW light in an optical fiber against mode field diameter. This curve is base on a theoretical value of 10W/um^2. We use a 10x safety factor on this maximum power to establish a safety limit for long-term operation. For a 10um 0.08NA single mode delivery fiber, the end cap is not mandatory at 150W of output power but reducing power density prevents dust attraction from the high intensity electrical field at the end facet. Since the end cap length is fixed, the divergence of the beam is higher for small MFD creating a bigger beam size at the end cap end and increasing the maximum power before reaching the air damage limit. This explains why the end cap maximum power handling decreased when you increase your MFD. However the actual design will be limited by the packaging power handling well before reaching the limit show on this graph.

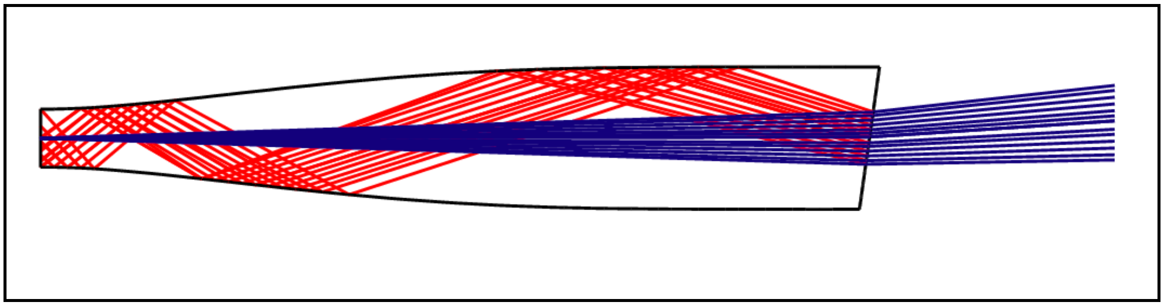


Figure 3. Two dimensions illustration of a 3 dimensional model, which is used to optimize the end cap design.

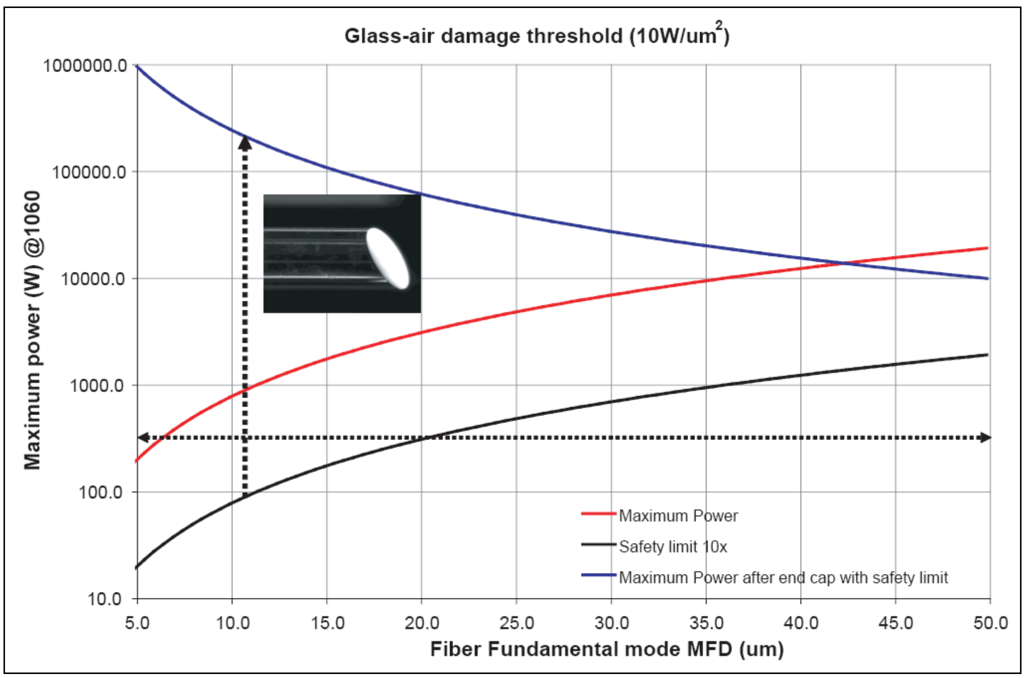


Figure 4. Air damage threshold curve with safety factor vs. mode field diameter of laser output fiber and end cap.

2- Preservation of optical properties of the beam:

In many applications, beam quality is an important characteristic that requires a certain level of attention. For example, close to Gaussian beam quality (M^2<1.1) is required for efficient up-conversion in the UV. Another reason would be to simplify focalizing in range finding applications. For coherent detection and up-conversion, polarized signal are often require. In these cases, polarization extension ratio (PER) of 20 dB or more must be maintained at the output of the fiber laser termination.

When simply attaching the end cap to the output of large mode area fibers (LMA fibers), no significant degradation of any of the optical properties is observed. Although, when packaging LMA fibers, which guide single mode light to the end cap, packaging can be a challenge. Stress due to the different anchoring bonds and stripping techniques used to achieve high cladding isolation can be problematic resulting in poor modal quality and loss of PER. By optimizing the packaging process, preservation of LP01 and maintaining an acceptable PER is possible. In the following figure, the M² measurement of a completely packaged end cap is shown. The modal quality remained acceptable for both axes: 1.10 and 1.16.

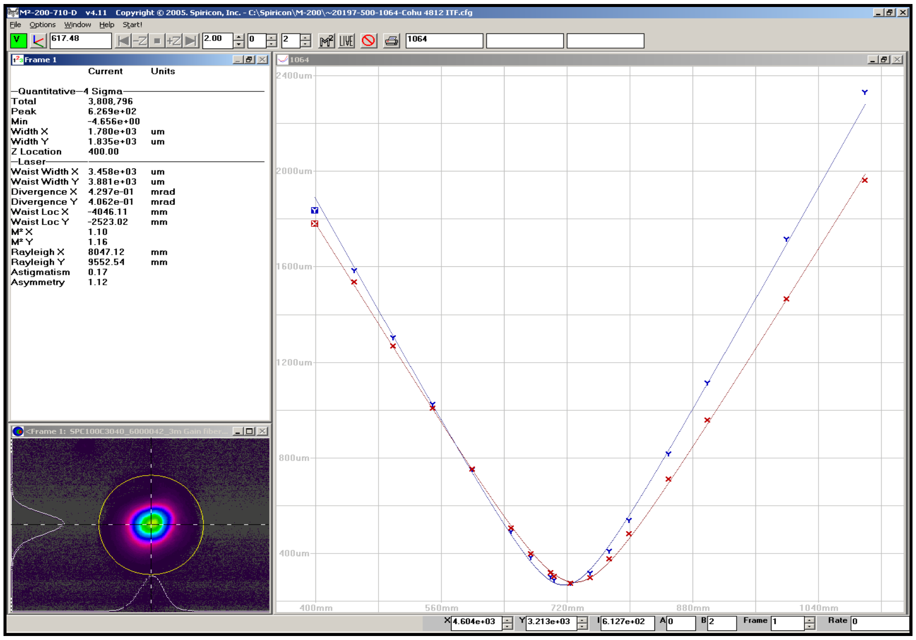


Figure 5. M² measurements of a completely packaged end cap.

3- Core to core isolation

As mentioned previously, when using a proper end cap design, any Fresnel reflections at the glass–air interface will not efficiently couple back into the fiber core, since the reflected beam diverges further on the way back to the core. This reduces the risk of having uncontrolled high peak power pulses of coherent signal light that could be re-injected in the cavity and damage the optical engines and there pumps.

There are many ways of defining and measuring the core-to-core isolation. In this section we will present 2 different measurements.

The first setup shown in Figure 6 was used to measure core-to-core (**LP01**) isolation due to the glass-air Fresnel reflection of the flat end cap. A broadband 1060nm sources with a 3dB coupler was used to inject and measure the reflection of the core light back in to the core. Using a mode field adapter (MFA) only LP01 was launched into a 20/400 DCF fiber to which an end cap was fused. The MFA also filtered out all modes except LP01 of the back-reflected light including cladding light. The end cap was polished flat (no angle). The measured core-to-core (LP01) isolation was over 35dB. The small difference between the theoretical value presented in section 2 (37dB) and the measurement performed here is due to measurement error.

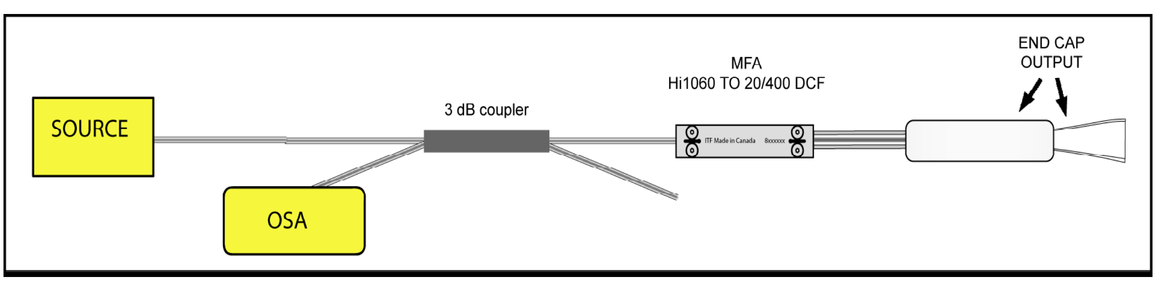


Figure 6. Reflection measurement setup for core-to-core (LP01) isolation.

A second setup, shown in figure 7, was used to measure core-to-core isolation by transmission. It must be pointed out that in this setup, the transmission is equivalent to 100% reflection (not only 4%). One end cap was used to launch into another end cap. This allowed measuring how much light was re-coupled back into the core (not only LP01) and how much was guided by the cladding without being stripped by the integrated cladding stripper. In order to differentiate the core from cladding light, which passes thru the end cap and guided in the fiber, index matching gel was applied on the glass. A differential measure, with and without gel, allowed quantifying the attenuation of the light that is launched in the cladding. With 100% transmission, the core-to-core isolation was 10,74dB. By adding 15dB of isolation (represents 4% reflection instead of 100% transmission) to the 10,74dB we obtain the 25.74dB core-to-core isolation of a flat end cap due to the air-glass Fresnel reflection.

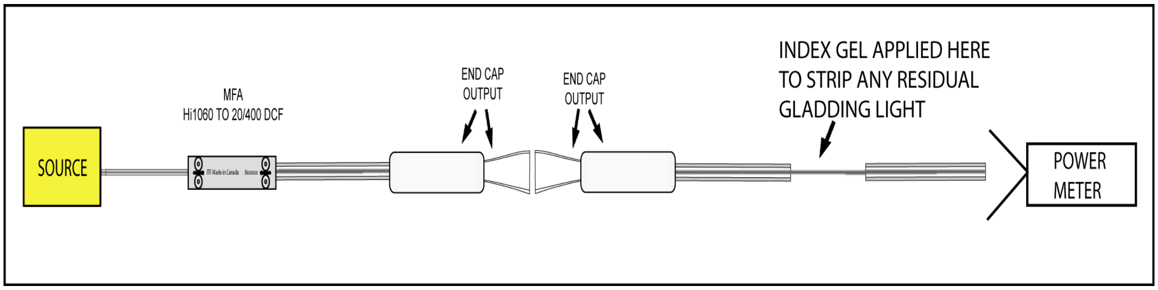


Figure 7. Measurement setup for transmission, core-to-core and core to cladding isolation.

4- Core to cladding isolation:

Emphasizing on high cladding isolation in an amplification configuration, which reduces the amount of cladding light being re-injected in the cavity, leads to the reduction of unwanted back traveling stray light amplification. In must be noted that the light being reflected back in the cladding is not only due to the air-glass Fresnel reflection but from any other reflection that could be generated by any outer materiel reflecting light back in end cap. No consideration is given to the scenario where bulk optics are used to collimate the beam on to a surface and this beam is reflected and refocused back into the core.

From the previous set up shown in figure 7 the core to cladding isolation was measured to be over 30dB. It must be noted that the difference between this isolation and the one presented in table 1 is due to the integrated cladding stripper that increases significantly the cladding isolation.

4. MANAGING UNWANTED LIGHT DUE TO HIGH ISOLATION

By achieving both high core-to-core and cladding isolation, the challenge was now to manage all this unwanted light. This unwanted light can represent hundreds of watts and must be managed adequately. The power handling was characterized by the capability of the device to handle dissipated optical power, rather than transmitted power. In order to characterize the behaviors of the end cap in high power applications, a special setup was necessary since the Fresnel reflection would only produce so many watts of power due to the limited available power. In the following setup shown in figure 8, the end cap absorbed and dissipated 63 watts of optical power while remaining at an acceptable temperature.

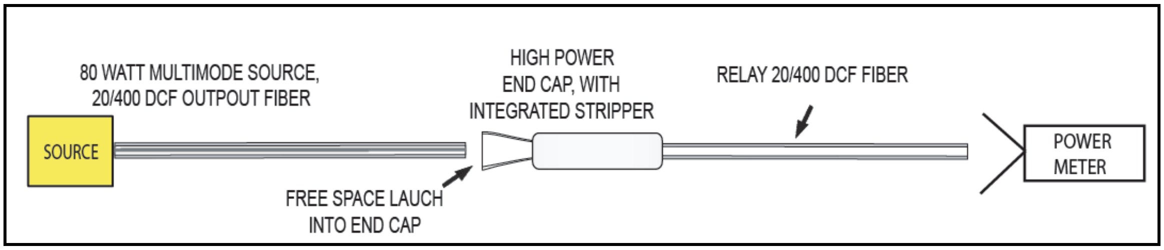


Figure 8. High power setup used to characterize the thermal performance of the end cap

The source used was a combination of multimode pumps spliced to a 32x1 TFB [8] allowing end pump coupling in the cladding of a 20-400 0.46 DCF relay fiber with more than 80 W of pump light at 915nm. The output numerical aperture (NA) was measured to be 0.46. The injection of the light was done free space into to flat end cap. We considered 96% coupling due to the Fresnel reflection. Since the launch fiber was 400um in diameter and the end cap diameter is 1060mm, no misalignment loss was considered.

While increasing the amount of light being launched in the end cap, a thermal camera was used to monitor the temperature of the end cap. Up to 63 watts was injected and dissipated in the end cap. An average isolation of 27dB was measured. The package end cap was attached to an actively cooled base plate and the hottest point was measure to be 77°C. This is mainly due to the lack of heat sinking of the glass tube that exist the high power package. By modifying the jigging required for the polishing process, the portion of the glass tube that exceed the package could be reduce significantly which would reduce temperature rise for the same amount of power dissipation.

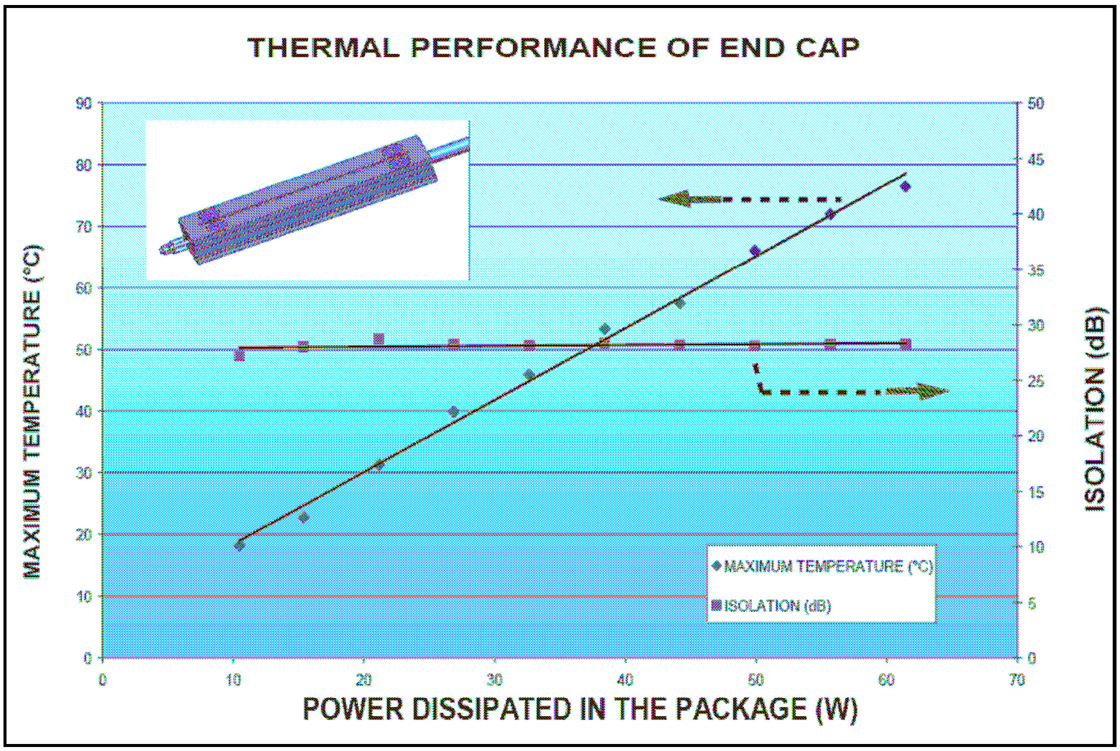


Figure 9. Temperature rise and isolation of the end cap when tested at high power.

5. CONCLUSION

High core and cladding isolation was measured with a flat end cap with the integrated cladding stripper. Results are summarized in table 2. The integrated cladding stripper is necessary to achieve high core to cladding isolation. High power testing of the component demonstrated an attenuation of 27dB and remained under a maximum allowable temperature while dissipating all of the 63 watts injected.

Core-to-core (LP01) 4% reflection	Core-to-core 100% transmission	Core-to-core 4% reflection	Core to cladding 4% reflection
< 35dB	10.74dB	25.74dB	< 30dB

Table 2. Summary of different isolations for the flat end cap

By accepting a peak operating temperature of 70°C, which corresponds to an dissipation of 50watts, this suggest that this end cap could guide up to 1.25KW of continuous power.

The above results suggest that understanding the mechanisms of optical loss for forward and backward propagating light in a end cap and the heat load that these losses generate is the key to deliver kilowatts of optical power and protect the integrity of the system. All these isolation will increase significantly when an angled end cap will be used. Applying AR coating will also have a positive effect.

4- References

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