Tapered fused-bundle splitter capable of 1kW CW operation

Alexandre Wetter[a], Mathieu Faucher[a], Michael Lovelady[b], François Séguin[a]
[a] ITF Laboratories, 400 Montpellier, Montreal, Québec, H4N 2G7, Canada;
[b] SPI Lasers UK Ltd, 3 Wellington Park, Tollbar Way, Hedge End, Southampton SO30 2QU

ABSTRACT

In order to test power-handling at 1kW, a special splitter component had to be developed to make use of available sources. A tapered fused-bundle (TFB) 1X7 splitter using a 1.00mm core diameter 0.22NA input fiber coupled to seven 400 micron core 0.22 NA output fibers was tested up to 860W at 976nm. Surface temperature rise was measured to be less than 15°C with active heat sinking. The above results suggest that understanding the mechanisms of optical loss for forward and backward propagating light in a TFB and the heat load that these losses generate is the key to producing multi kW components, and demonstrates that reliable kW-level all fiber devices are possible.

Keywords: High power, tapered fused bundle, packaging, reliability, fiber laser

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 [1,2]. 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 [3-4], relying for the most part on the use of discrete bulk components for coupling in and out of the fiber gain medium.

Tapered fused bundle (TFB) couplers allow monolithic integration of devices for deployment in the field. Characterized by intrinsically low transmission loss, these all-fiber components are well suited to combine signal and pump light. Power handling at two hundred Watts has been demonstrated [1]. The most meaningful benchmark, when considering the power handling of the device, is the capability of the device to handle optical power loss, rather than transmitted power. This approach provides a more accurate estimate of feasible power levels and allows increased power handling by addressing thermal management and optical loss reduction issues concurrently.

It this work, the origin of optical loss and its impact on package temperature rise in realistic high power operating conditions is studied and demonstrated.

This paper is structured as follows. In section 2 a brief description of a TFB is given. In section 3 we will compare thermal characterization of TFB's under conditions of passive vs. active heat sinking, with and without 4% end-cleave back reflection. In section 4 we discuss the importance of minimizing optical loss and understanding the origins of these losses and their path. Finally, in section 5 we discuss the performance of a kilowatt level device.

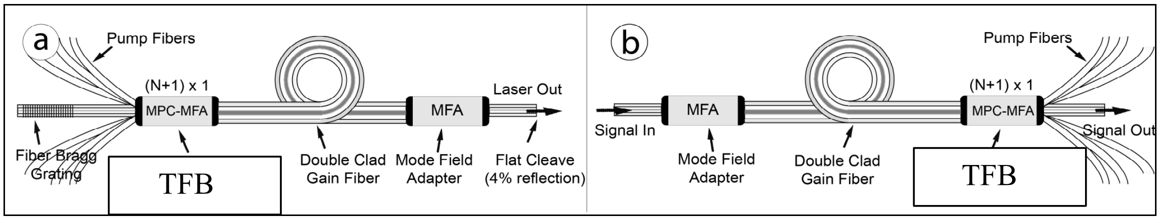

Figure 1 Example of a fiber laser (a) and amplifier (b) designs in which tapered fused bundle (TFB) couplers are integrated.

2. TAPERED FUSED BUNDLE (TFB) COMBINERS

Tapered fused bundle (TFB) combiners play an increasingly prevalent role in fiber laser integration. A typical fiber laser and a fiber amplifier with their different components such as a TFB couplers to combine the pumps, double clad (DCF) gain fiber as the gain media and mode field adapters (MFA) are illustrated in Figure 1.

Figure 2 shows a TFB structure with its anchoring bonds and the metallic package in which the structure is embedded. These anchoring bonds (structural adhesives) constitute the main source of heat in TFB devices when they absorb light (optical loss). We optimized the metallic package for thermal dissipation of optical power loss, while ensuring that optical properties are maintained during qualification testing. We developed a specially instrumented TFB package using Bragg sensors, allowing us to establish the relationship between bond temperature and case temperature. The Bragg sensors are inserted through the anchoring bond in the package and used to generate a temperature profile. This relation is used to predict the inner temperature of non-instrumented devices by tracking the device surface temperature. Bragg sensors have previously been used for temperature assessment under high power illumination, where thermocouples suffer from high absorption of the optical field [5].

We demonstrated in previous work [6] that the best strategy to decrease thermal impedance in the TFB package is to 1) minimize the thickness of adhesive between the fibers and the inner wall of the package, 2) increase the adhesive's transparency and thermal conductivity while 3) maximizing contact of the adhesive to a material that has the largest possible thermal conductivity.

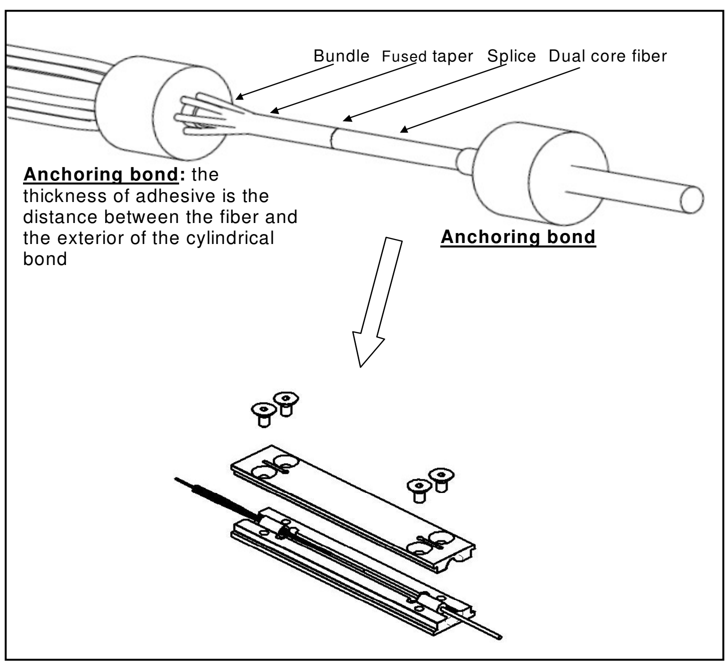

Figure 2 Typical TFB structure with anchoring bonds (structural adhesives). These bonds constitute the main source of heat in tapered fused bundle (TFB) devices when they absorb light (optical loss).

3. THERMAL CARACTERISATION.

3.1 Comparing thermal characterizations

We demonstrated in previous work [6] that a temperature elevation of 1.1°C/W for forward propagating pump light with no back reflection can be achieved using passive heat sinking. The same component with a straight cleave (4% back reflection) had a thermal impedance of 1.63°C/W when considering losses from forward and backward propagating light. Given the very low losses in TFBs for forward propagating pump light, the Fresnel reflection from the fiber end face re-injects a significant amount of light in the backward direction. A portion of this back reflection is dissipated in the package and generates heat. We show in section 3 that components have different losses by design for backward and forward propagating light.

The demonstration with over 300 watts of pump power in an instrumented package is shown below. An important change was introduced in this new thermal characterization: the component was actively cooled at 15°C on the bottom surface vs. passive heat sinking in previous work [6]. The thermal characterization of a combiner, optimized to minimize forward propagating pump loss and tested at more than 300W of input power is illustrated in Figure 3. The device is tested in 2 different configurations: with and without 4% end-cleave back reflection.

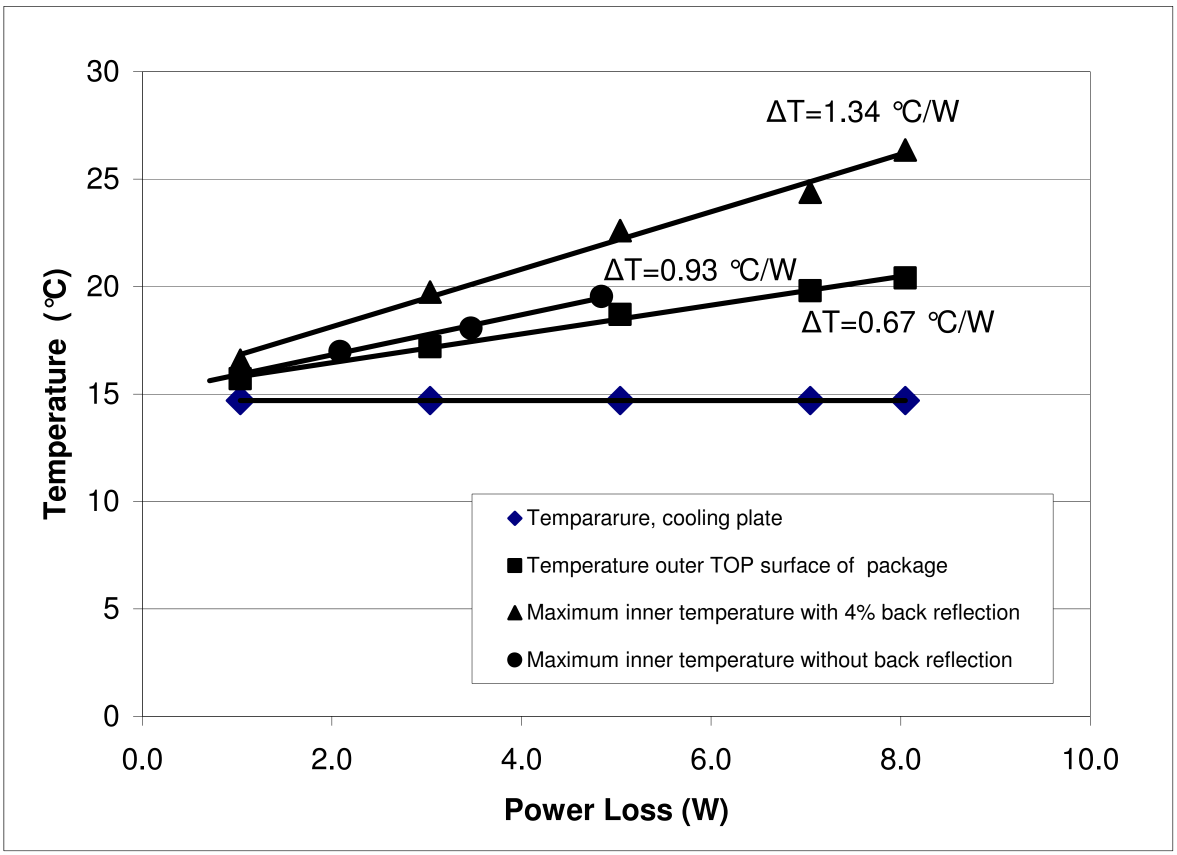

Figure 3 Thermal characterization: temperature at the hottest point vs. optical power loss for a packaged TFB, actively heat sunk, in forward only and forward+backward propagating pump configurations

The slopes of temperature rise as a function of dissipated power obtained in previous work [6] and the results shown in figure 3 are summarized in table 1. The slopes presented here are lower than those from previous work due to the active cooling. The trend is true for both configurations, with and without back reflection. As indicated in table 1, active cooling will reduce the temperature rise by about 19%. This reduction could easily have been improved if active cooling was applied on additional surfaces. Both devices have approximately the same heat load increase when backward propagating light is added to the forward propagating light. This backward propagating light will have a different loss path than forward propagating light and generate additional heat. The type and path of the lost light dictates the thermal impedance of the packaged device.

Component thermal impedance °C/W	Without back reflection	With back reflection	Heat load INCREASE
Passive heat sinking	1.10	1.63	47%
Active heat sinking	0.93	1.34	44%
Slope (°C/W) DECREASE	19%	18%	

Table 1 Difference in thermal impedance between active and passive heat sinking

The thermal characterization of the device shown in Figure 3 also demonstrates the constant relationship between the temperature of the outer top surface and the inner maximum temperature. The inner temperature rises at twice the rate of the outer temperature. It is now possible to approximate the inner maximum temperature of a non-instrumented component by measuring the outer temperature. For this to be relatively accurate, the component must be optically characterized, actively cooled at 15°C on the bottom surface and have a good thermal contact with the cooled plate.

3.2 Thermal impedance

As mention above, the difference in thermal impedance for forward and backward propagating light is due to the origin of the losses and the path of loss mechanisms. In general, brightness conservation losses will result in pump light leaking into the cladding that will potentially be stripped by anchoring bonds and generate a heat load. This topic is widely addressed in section 4. Other types of loss occur at the splice and are scattered inside the package to be eventually absorbed by the sidewalls and in the bulk of the anchoring bond.

The heat load generated depends strongly on the type of losses in the forward and/or backward propagating cases. Accordingly, different thermal impedances are observed in backward and forward directions.

Since backward propagating light is often unavoidable, the effective thermal impedance of the component is 1.34°C/W when actively cooled as indicated in table 1. Given that the maximum internal operating temperature is 70°C, when actively cooled at 15°C, approximately 41 watts of loss is the maximum dissipated optical power allowed. Figure 7 shows the maximum input power for a typical combiner assuming 1.5% loss in forward and about 20% loss in backward propagating light as a function of the back reflection.

In the case where no back reflection is present, 41 watts of dissipated power represents about 2700 watts of input power. Some applications such as welding can produce up to 30% of back reflection. When used in co-propagating and counter-propagating pump lasers or amplifier applications, a significant amount of backward propagating light is produced. As shown in figure 7, the amount of back-reflected light significantly reduces the maximum input power allowed. This reduction is dramatic for components that have significant loss for backward propagating light. In order to allow kilowatts of input power, optical losses of backward propagating light must be addressed.

The same challenges associated with back-reflected power in TFBs are also an important issue when designing splitters. Understanding and minimizing optical loss is key for all high power components.

4. SOURCES OF OPTICAL LOSS

4.1 Brightness conservation

In multimode combiners or splitters, all modes are not always transmitted with the same loss in forward and backward directions. Those losses are related to the brightness conservation ratio (B).

$$B = \frac{n_i (NA_i)^2 A_i}{n_o (NA_o)^2 A_o} \tag{1}$$

n_i = Number of input fibers for a combiner or a splitter

n_o = Number of output fibers for a combiner or a splitter

A = Area of one fiber (input or output)

NA = Numerical aperture (input or output fiber)

B = Brightness ratio

In general, to minimize pump loss, a typical component is designed with a brightness ratio smaller than 1. This ensures a good transmission for any modes, fully filled excitation, in the forward direction. But consequently, the transmission of the component will be lossy for some of the modes, generally the high order modes, in backward direction. By etching the fibers, lower loss is obtained in both directions. The subject of etching will be addressed in section 4.3. To be fully symmetric the component should have a brightness ratio equal to 1. Figure 4 shows the losses in both directions for 2 different components: using etched fibers and using non etched fibers.

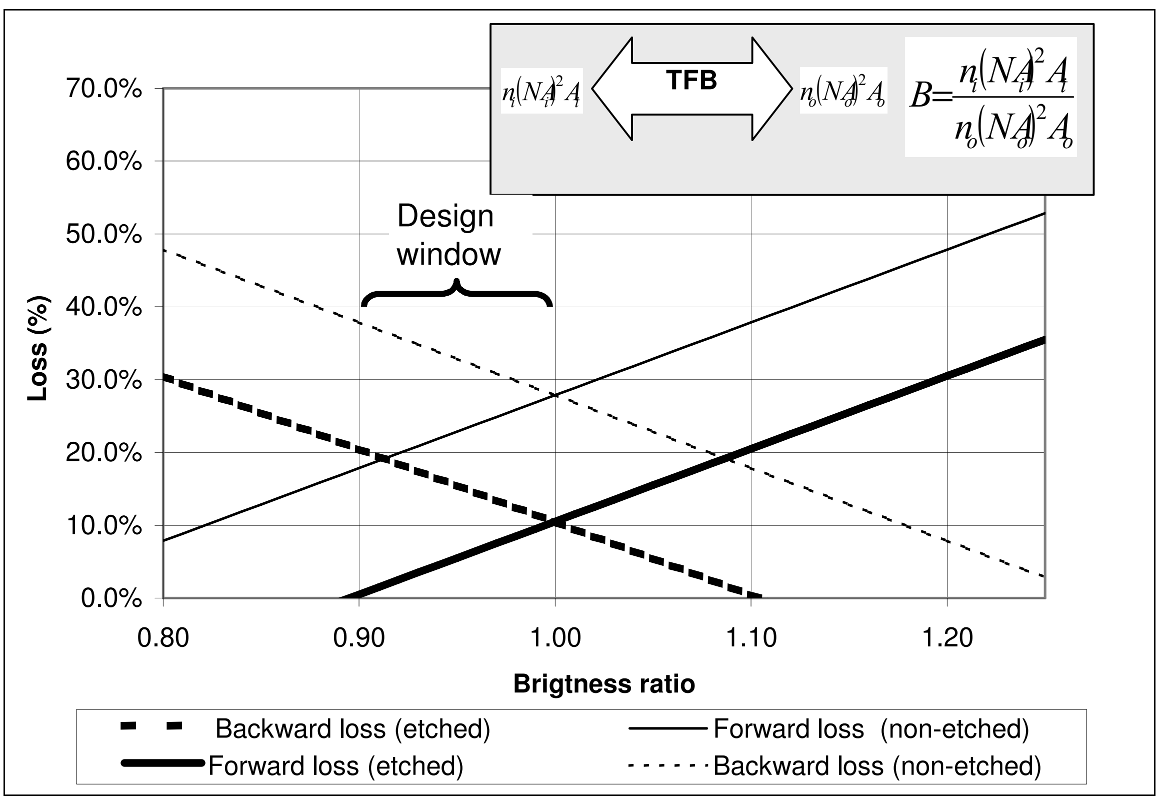

Figure 4 Optical loss in both directions for 2 different devices: one using etched fibers the other non-etched fibers.

4.2 Numerical aperture transformation

In order to maintain brightness preservation in a given optical design, a balance must be achieved between the numerical aperture and the area through which the light travels. Figure 5 describes the numerical aperture transformation of pump light traveling in the component in forward and backward propagation configuration. This must be understood in order to apply the brightness conservation relation. Calculated values of losses due to numerical aperture mismatch are shown as an example in Table 2.

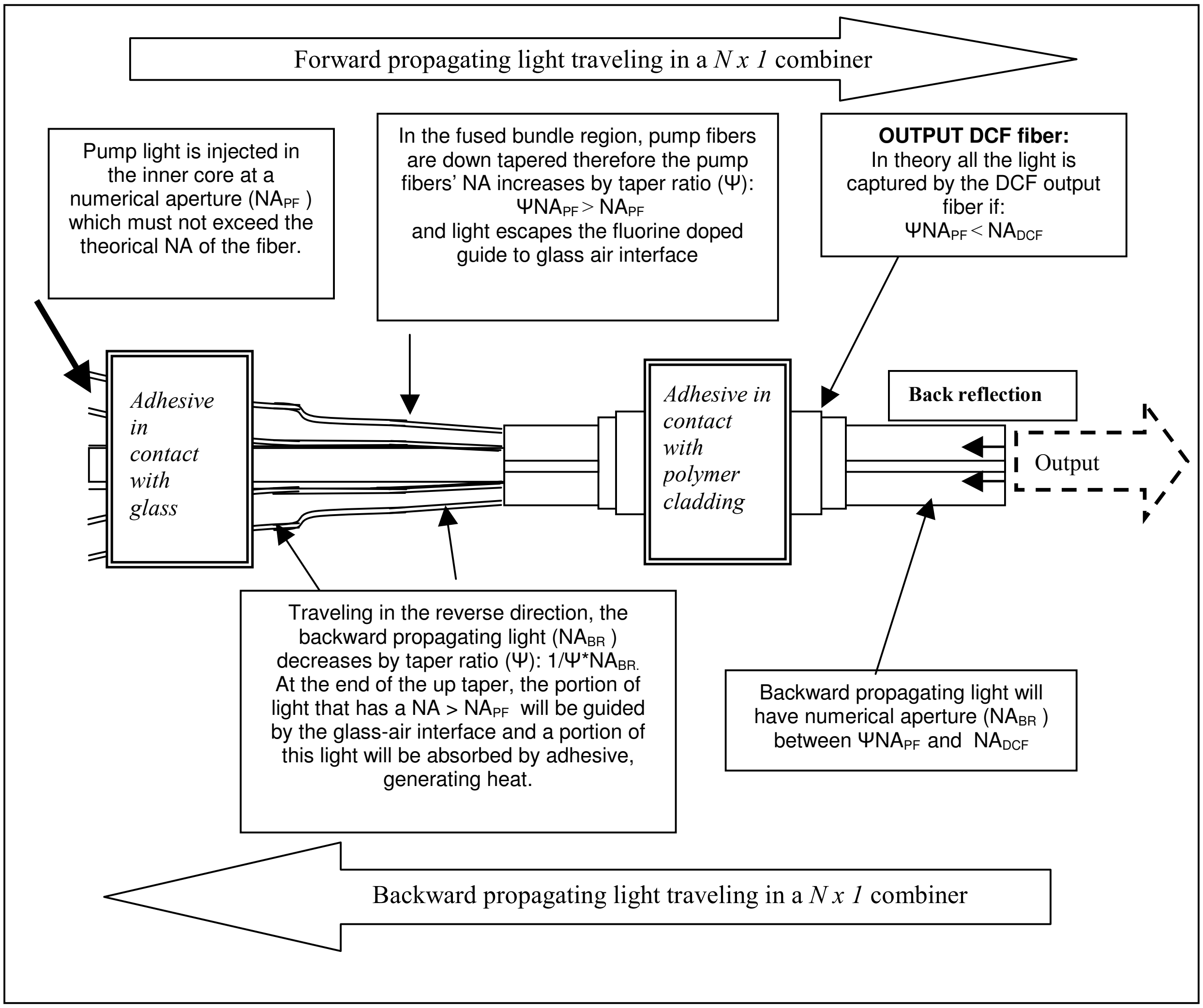

Figure 5 Description of numerical aperture transformation in a TFB.

4.3 Area mismatch

The second aspect that must be managed is area mismatch. When light travels from the single fiber to the bundle, a portion of the light will be injected in the fluorine doped glass cladding that will be stripped or guided elsewhere by polymer cladding or anchoring bonds. This translates in to significant optical losses and generates heat. To minimize these losses, the fibers are chemically etched to remove the fluorine doped glass cladding, revealing the inner core, Figure 6 shows the difference between 2 bundles. The first bundle is made of 7 non-etched fibers. The fluorine doped glass cladding can be distinguished from the pure silica core. The second bundle is made from 7 etched fibers. All the area is pure silica. By continuing to fuse the bundle, the geometry becomes circular. The area mismatch with the single fiber is then minimized. Calculated values of losses due to area mismatch are shown as an example in Table 2.

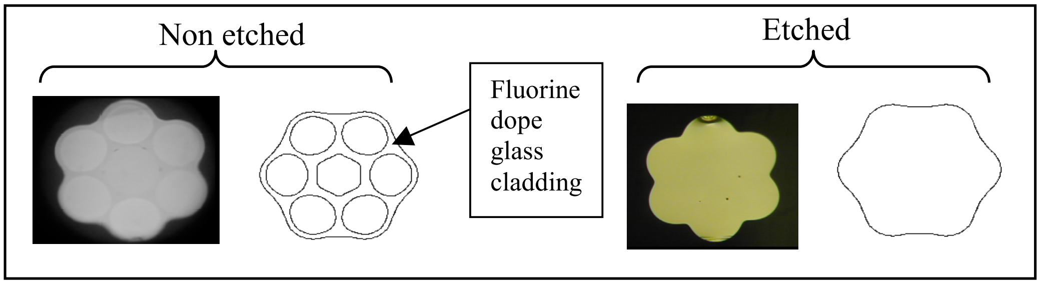

Figure 6 : Picture and sketch showing the difference between an etched and non-etched fused bundle.

4.4 Loss breakdown of a typical component

A summary of the main sources of optical losses generating heat loads is presented in Table 2. In order to appreciate the importance of chemically etching the fibers, a breakdown of the losses for three different components is shown:

- Combiner 7 to 1, optimized for low forward propagating light loss
- Splitter 1 to 7, using non-etched fibers
- Splitter 1 to 7, using etched fibers

	Type of component			Combiner 7 to 1 non-etched	Splitter 1 to 7 non-etched	Splitter 1 to 7 etched
	Typical component loss (%) in the direction of pump light			1.50%	28.00%	10%
	Type of loss	Type of Relationship	Direction of light in component	200/220 0.22 --> xx/400 0.46	1000/1060 0.22 -> 400/440 0.22	1000/1060 0.22 -> 400/440 0.22
Brightness conservation	NA mismatch	$T = \left(\frac{NA_{output}}{NA_{inputl}} \right)^2$	forward propagating light	$\approx 0\%$	$\approx 9\%$ [c] OR	$\approx 9\%$ [c] OR
			backward propagating light	$\approx 0\%$ [a]	$\approx 9\%$ [c]	$\approx 9\%$ [c]
	Area mismatch	$T = \frac{A_{output}}{A_{input}}$	forward propagating light	$\approx 0\%$	17.4%	$\approx 0\%$
			backward propagating light	17.4%	11 %	$\approx 0 \; or \; 11\%$ [b]
	Lateral misalignment	$T = 1 - \frac{2x}{\pi \cdot r}$	Both directions	$\approx 0\%$	$\approx 0\%$	$\approx 0\%$
	Angular misalignment	$T = 1 - \frac{\theta}{\pi\sqrt{2\Delta}}$, see ref. [7]	Both directions	$\approx 0\%$	$\approx 0\%$	$\approx 0\%$
Scattering	Micro bending		Both directions	1.5%	1.5%	1.5%
	Macro bending	$T = e^{-\gamma \cdot z}$, see ref. [8]	Both directions			
	Absorptive defects		Both directions			
a- NA transformation in tapered fibers are bi-directional.						
b- There will be no mismatch in area if all fibers are modified: INPUT and OUTPUT						
c- Numerical aperture mismatch of 0.01. The loss (mismatch) is only in one direction						

Table 2 Example of 3 different components with their respective breakdown of optical loss

There are significant differences between forward and backward propagating light losses in a component:

- A slight numerical aperture mismatch of 0.01 results in significant losses of 9%. In order to minimize this type of loss, input and output fibers can be drawn from the same preform and /or ordered with tight tolerances.
- When comparing a splitter built with etched fibers vs. one built with non-etched fibers, the loss due to area mismatch is important.
- All components have about 1.5% of scattering loss due to the fabrication process and defects.

Note: Pump light is addressed here but signal light is not. The latter is mainly confined to the core of the signal fiber and does not interact much with the adhesives. There are other issues to be addressed with signal light, however it is beyond the scope of this paper.

4.5 Potential of an optimized design

By understanding how to obtain relatively good optical properties in both directions, optical designs that allow over 1 kilowatt of input power are possible even with 30% back reflection as shown by the dashed line in figure 7.

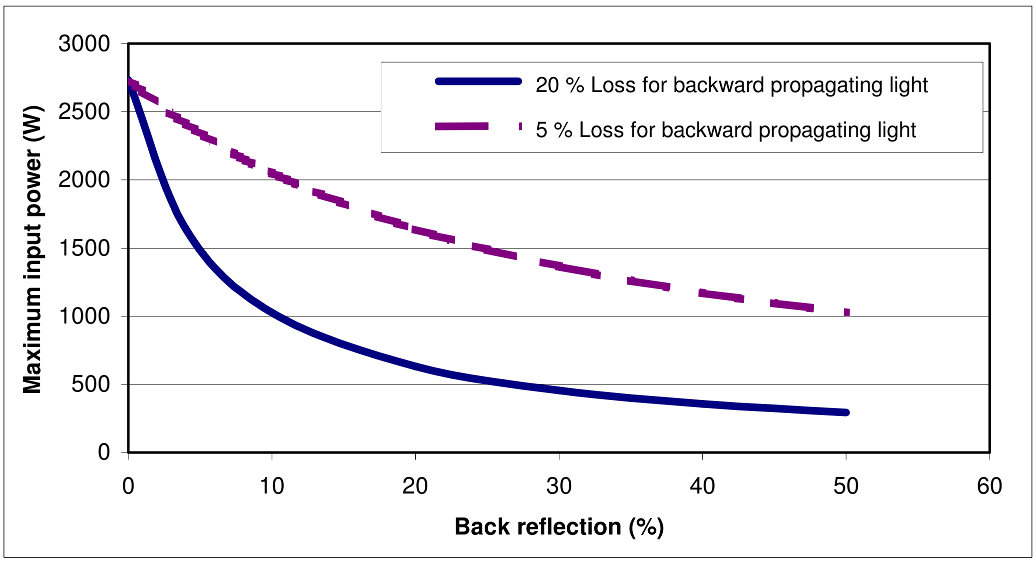

Figure 7 Maximum input power of a typical TFB combiner actively cooled at 15°C as a function of back reflection

5. KILOWATT DEMONSTRATION

In order to test power-handling performance up to 1kW, a special splitter component was developed to make use of available sources. The demonstration was done at SPI Lasers UK Ltd. Using the brightness conservation techniques discussed above, a 1X7 TFB splitter using a 1.00mm core diameter 0.22NA input fiber coupled to seven 400 micron core 0.22 NA output fibers was tested up to 860W at 976nm. Surface temperature rise was measured to be less than 15°C with active heat sinking.

Given the sensitivity of the device to back-reflected light, special end termination techniques had to be used. The device was non-instrumented, meaning that the inner temperature could only have been estimated by external temperature using the relationship established with the specially instrumented TFB presented in this paper. For the demonstration, both top and bottom surfaces are actively cooled as shown in Figure 8. The physical sizes of the fibers are such that a reduced amount of adhesive was needed to embed the TFB in the package. This reduces the thermal barrier (anchoring bonds), hence reduces the thermal impedance as mentioned in section 2. The relationship established with the specially instrumented TFB does not strictly apply to this device and setup due to the different internal thermal impedances.

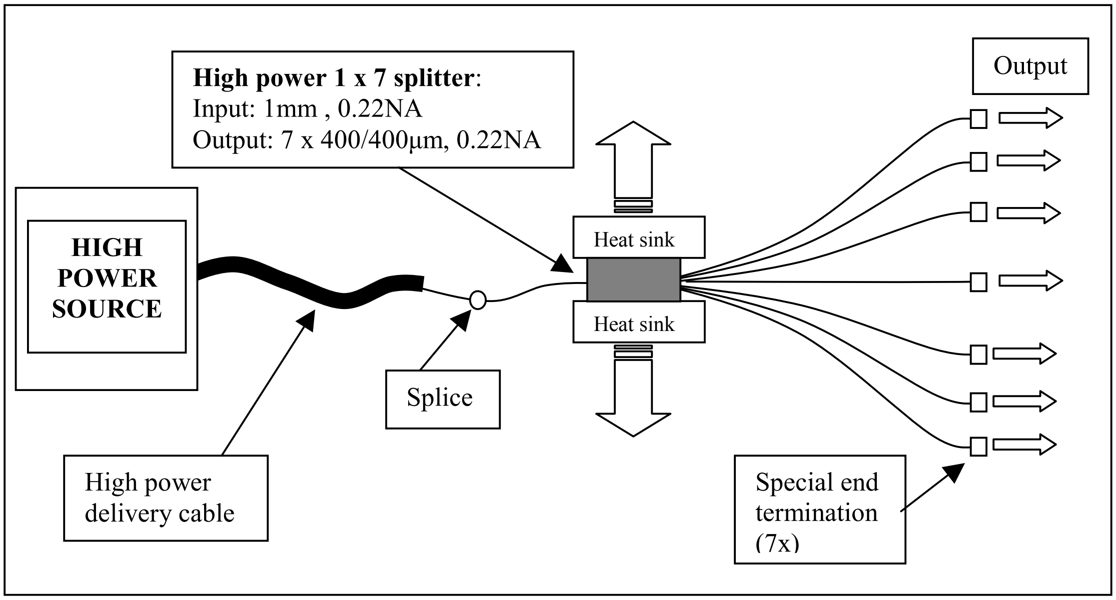

Figure 8 Setup used to test power-handling performance up to at 1kW

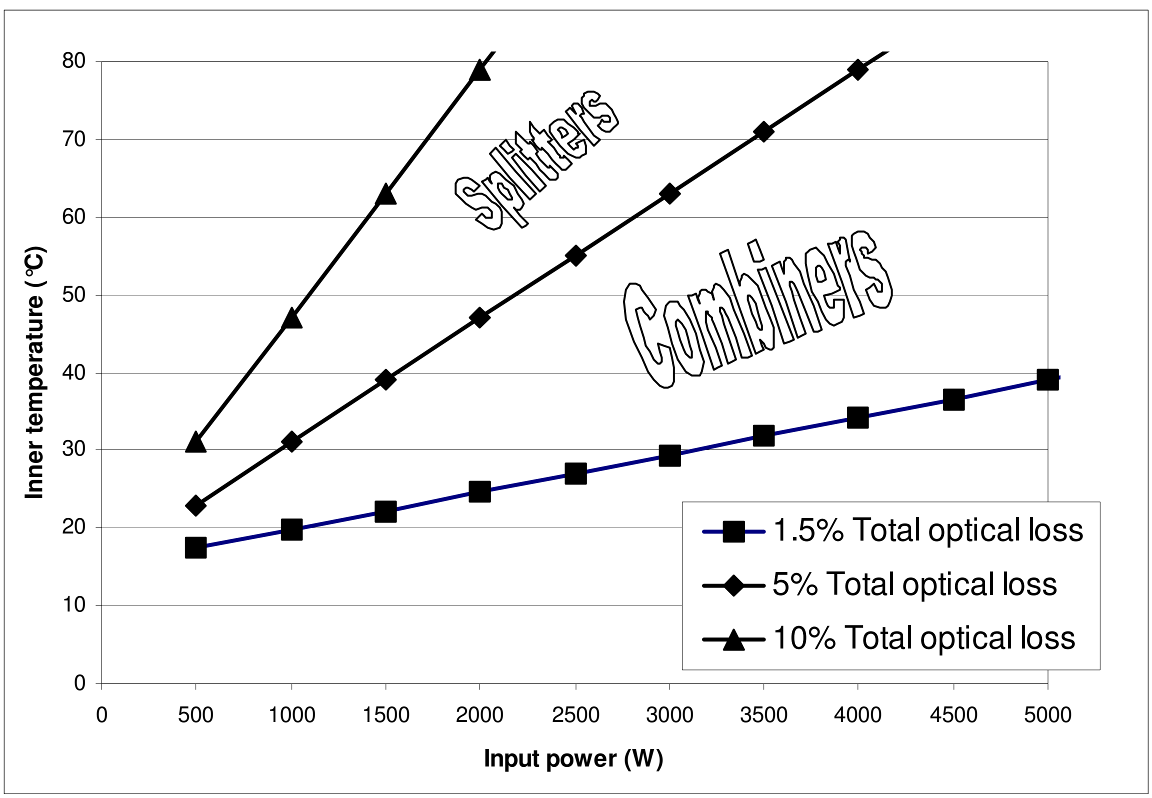

Figure 9 Maximum input power in a component that is characterized by a thermal impedance of 0.32°C/W

The insertion loss of the component is about 11%. Therefore, at 860 Watts of input power, 95 Watts is dissipated. With the surface temperature rise measured at 15°C and the relation established between the inner and outer surface temperature (from figure 3), the inner temperature rise is 30°C, hence, the calculated thermal impedance of this device is approximately 0.32°C/W. However we believe that the relationship between outer and inner temperature is less than 2 due to the additional cooling applied and the reduction in thermal impedance due to reduced adhesive thickness. A thermal impedance of approximately 0.25°C/W is probably a more realistic estimate.

With this thermal impedance, components sustaining multi kilowatt are possible. Figure 9 shows maximum predicted input power in components with different losses that are characterized by a thermal impedance of 0.32°C/W. The typical loss for a combiner is in the 1.5 to 5% range, 5 to 10% for a splitter, showing multi kilowatt operation is possible in both cases.

6. CONCLUSION

We presented the thermal characterizations of a device under different conditions in order to define the maximum rating of TFB when using ITF's high power packaging for Kilowatt power handling. We discussed the importance of minimizing optical loss in both directions and demonstrated that kW-level operation is possible. The results indicate that minimizing optical losses in both directions and minimizing the thermal impedance is the key to the multi kW components. Obtaining good optical properties in both propagation directions is not easily achieved and remains a challenge. Further work needs to be done in order to quantify the variation of the thermal impedance in regard to the thickness of adhesive between the fibers and the package.

7. REFERENCES

[1] F. Gonthier, L. Martineau, N. Azami, M. Faucher, F. Seguin, D. Stryckman, A. Villeneuve, 'Hig-Power all-fiber components : the missing link for high power fiber lasers', Fiber Lasers: Technology, Systems and Applications, L.N Durvasula, pp. 266-276, Proceeding vol. 5335, SPIE, Bellingham, WA, 2004.
[2] F. Gonthier, "All-Fiber® pump coupling techniques for double-clad fiber amplifiers and Lasers", TFII1-3 Cleo Europe 2005.
[3] S. Norman, M. Zervas, A. Appleyard, M. Durkin, R. Horley, M. Varnham, J. Nilsson, Y. Jeong, "Latest development of high power fiber lasers in SPI", Fiber Lasers :Technology, Systems and Applications, L.N Durvasula, pp. 229-237, Proceeding vol. 5335, SPIE, Bellingham, WA, 2004.
[4] J. Nilson and Al., "High power fiber lasers", High power fiber lasers, paper OTuF1OFC 2005 Technical digest
[5] V. Goloborodko, S. Keren, A. Rosenthal, B. Levit and Moshe Horowitz, "Measuring temperature profiles in high power optical fiber components", Appl. Opt., 42(13), May 2003
[6] F. Séguin, A. Wetter, L. Martineau, M.Faucher, C.Delisle and S.Caplette, "Tapered fused bundle coupler package for reliable high optical power dissipation", Proc. SPIE Vol. 6102, 61021N, 2006
[7] H. Tsuchiya, H. Nakagome, N. Shimizu and S. Ohara, "Double excentric connector for optical fiber", Appl. Opt., 16(5),PP.1323-1331, 1977.
[8] A. Snyder and J. love, Optical Waveguide Theory, pp. 182-184, Chapman and Hall, New York , 1983.