(6+1) ×1 Fiber Combiner based on Thermally Expanded Core Technique for High Power Amplifiers

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ABSTRACT

A high-efficiency pump-signal combiner for high power fiber amplifiers based on thermally expanded core (TEC) technique is reported in this paper. TEC technique is used to fabricate mode-field adapter which allows optimization of signal fibers in a monolithic (6+1) ×1 fiber combiner. The combiner is fabricated by connecting a tapered fiber bundle (TFB) to a passive 25/250 (NA=0.06/0.46) double-clad fiber (DCF). By this method, the coupling efficiency of SMF-28 signal fiber at 1064nm improves from 54% to 92.7%. The average pump coupling efficiencies of six 105/125 (NA=0.15) fibers are measured to be 96.7% at 976nm. Furthermore, the average signal transmission efficiency is around 93.3%. The fabricated fiber combiner is spliced to an Yb-doped DCF for use as an all-fiber amplifier. The slope efficiency is measured to be 71.6%.

Keywords: pump-signal combiner; thermally expanded core (TEC) technique; all-fiber amplifier

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1 INTRODUCTION

Pump-signal fiber combiners are critical components for high-power all-fiber lasers and amplifiers. This so called (N+1) ×1 fiber combiner consists of a tapered fused bundle (TFB) and an output deliver fiber. In a (N+1) TFB, N represents the number of pump fibers and 1 is signal fiber. To keep good beam quality, seed-through fibers are usually single mode fibers (SMFs), which have small core diameters as well as small mode-field diameters. In contrast, output deliver fibers are usually large core double-clad fibers (DCFs) with relatively large mode-field diameters [1-2]. To fabricate a TFB, the signal fiber is fused and tapered. After tapering, the core diameter of signal fiber becomes smaller. This large mode-field mismatch leads to low coupling efficiency of signal fiber. Hence, there is a need for mode-field adaptors to convert the fundamental mode from signal fibers to output DCFs [3-6].

Several approaches of mode-field adaptors for pump-signal fiber combiners have been reported. The most frequently used method is a tapered fiber. The taper is fabricated by immersing a DCF in hydrofluoric acid. The etching process is very complex and the quality of the surface of etched fibers is very important to the transmission loss [7-10]. The second approach reported is based on vanishing core technology where a special DCF is used as a mode adaptor for a (6+1)×1 combiner. The DCF is tapered for controlling the mode field diameter (MFD) by changing the refractive index difference [11].

Thermally expanded core (TEC) fibers have been reported very early to reduce the coupling loss between SMF and large mode area fiber. By heating SMF, the germanium dopant in the core diffuses to the fiber clad, then the MFD is enlarged. Mode-field mismatch loss can be reduced effectively using this technique [12-17]. TEC technique is also proposed to reduce the signal loss in (N+1)×1 fiber combiners [18].In our previous work, we also fabricated pump-signal combiners using TEC technique [4].

In this paper, we applied TEC technique to the fabrication of a monolithic (6+1)×1 pump-signal fiber combiner by another bundling method , which is different from Reference [4]. Firstly, we introduce the fabrication process of signal feed-through fiber combiner. Secondly, we analyze the power propagation efficiency of the feed-through fiber theoretically and compare this

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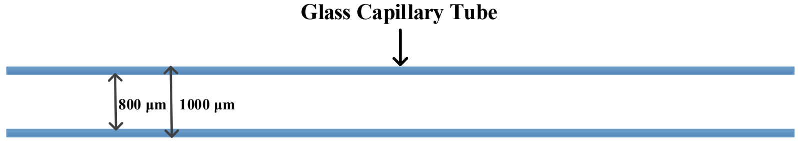
with the experimental measurement. Then, we introduce the TEC technique ,and also the process of fabricating a TEC fiber and fiber combiner with a TEC signal fiber. At last, an all-fiber amplifier system seeded at 1064nm is built by splicing an Yb-doped 25/250 DCF to the output deliver fiber of our fabricated combiner.

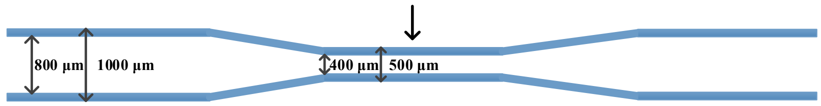
2 THE FABRICATION PROCESS OF PUMP-SIGNAL FIBER COMBINER

There are two main methods for bundling fibers in the process of fabricating an end-pump fiber combiner. One method is twisting fibers between two clamps by an angle with their polymer coating stripped off. The (8+1)×1 pump-signal fiber combiner reported by Qirong Xiao is fabricated by the this method [3-4]. The other method is using a capillary tube to make a fiber bundle [5-6]. This method can avoid the torsional stress caused by twisting fibers and also its drawback of generating more heat under high power laser and more easily cracking when fiber diameters are small. For high power laser and high stability, we choose the second method. Furthermore, it's easier to control the cleaved diameter of tapered fiber bundle, as there is no need to cleave at the waist of the bundle.

Our fabrication process is described in Fig. 1. As shown in Fig.1. (a) and (b), a glass capillary tube with an inner diameter of 800 μm and outer diameter of 1000 μm is tapered with a taper ratio of 1/2. Fig.1. (c) describes the bundling process. One signal fiber (SMF-28) and six multimode pump fibers (105/125, NA=0.15) are inserted into the tapered tube. To ensure the signal fiber in the center of the fiber bundle, we use a special clamp. The glass tube is fused and tapered the second time (taper ratio is 2/3) together with the fiber bundle. To reduce the tapering caused loss, the tapering process is required to be adiabatic. It's demanded that the length of tapered region in our fabrication process should be long enough. The fused fiber bundle is cleaved at a proper diameter to match the diameter of output deliver fiber and then spliced to a passive double-clad fiber.



(a)



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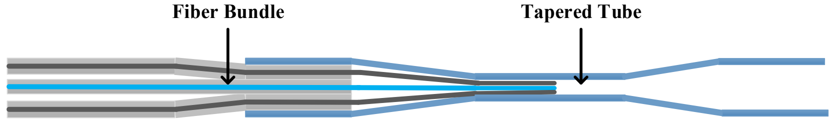

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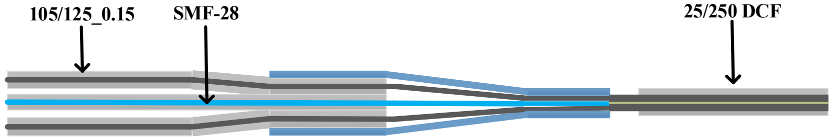


(d)

Figure 1. Schematic of combiner fabrication process((a) is a glass capillary tube (b) is a tapered tube(c) is the bundling process (d) shows a tapered and cleaved fiber bundle splicing to an output fiber).

3 THEORETICAL ANALYSIS OF PUMP AND SIGNAL TRANSMISSION LOSS

For a tapered multimode fiber, assuming adiabatic tapering, according to the brightness conservation, the numerical aperture (NA) at the input and output end can be derived using the input core diameter Din and output core diameter Dout [19].

$$D_{in} \times NA_{in} = D_{out} \times NA_{out} \tag{1}$$

The core diameter of tapered pump fiber is 70μm, so the calculated NA based on Equation (1) is 0.225, which is small than NA of the output fiber (NA=0.46). Basically speaking, our fabrication design is feasible. Numerical Analysis of pump transmission efficiency of our combiner by beam propagation method show that the total power efficiency is above 99%. And the measured efficiency is also very high with an average value of 96.7%.

Then, we consider the signal transmission efficiency. The splice loss of two connected fibers can be estimated based on mode-field diameter when the mode field is approximately a Gaussian function. The connection loss between their mode-field radius (ω_1, ω_2) is described as following equation [20],

$$Loss(dB) = -10\log_{10}\left(\frac{2\omega_1\omega_2}{\omega_1^{\,2}+\omega_2^{\,2}}\right)^2 + 4.343\frac{2\delta^2}{\omega_1^{\,2}+\omega_2^{\,2}} + 4.343\left(\frac{2\pi n}{\lambda}\right)^2 \frac{(\omega_1\omega_2)^2}{2(\omega_1^{\,2}+\omega_2^{\,2})} sin^2\theta \quad (2)$$

Where δ is the lateral core offset and θ is the angular misalignment of two fibers.

If we neglect the effect of the lateral offset and the angular misalignment, the first term of Equation (2) indicates that the splicing loss will be very low when the mode field diameters of two fibers are similar. We calculate the MFDs of two kinds of fibers (NA=0.14 and NA=0.06) with different diameters in Fig.2. The core diameter of signal fiber (NA=0.14) changes from 8 μm to 5.3 μm. According to Equation (2), the calculated loss of tapered signal fiber (MFD=5.95 μm) and output deliver fiber (MFD=21.45 μm) is 5.77 dB and the corresponding efficiency is 27%. This result only considers the power of LP01 mode, and this is different from the measurement in experiment.

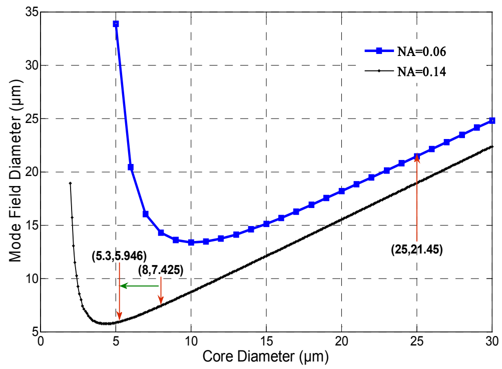


Figure 2. Relationship between mode field diameter and core diameter of fibers with NA=0.06 and NA=0.14

Also by beam propagation method, we monitor the coupling efficiency of the total power, the LP01 mode power and the LP02 mode power at 1064nm when the launch field is single-mode Gaussian beam. As depicted in Fig. 3, when monitoring total power, the coupling efficiency is only 53% in theory. The calculated result of equation (1) is described as the second graph line of Fig.2. It can be noticed that this mode-field mismatch also excites LP02 mode.

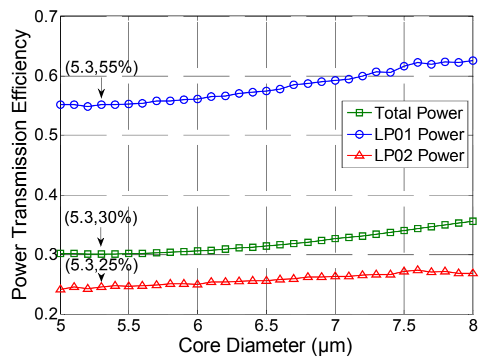


Figure 3. The monitor power transmission efficiency of tapered SMF-28 to a 25/250 DCF

4 THERMALLY EXPANDED CORE TECHNIQUE

To reduce the mode-field mismatch loss caused by small MFD of tapered signal fiber, TEC technique is used to enlarge the MFD of SMF-28. Theoretical analysis of TEC technique has been reported by many researchers [12-17]. By heating SMF, the germanium dopant diffuses from core to the clad of fiber. Thus, the distribution of the dopant is a function of radial position, heating time and temperature of the flame. The refractive index profile of TEC fiber is in proportional to the distribution function, which is a Gaussian function along the radial position and can be expressed as Equation (3). The sufficient thermal diffusion part of the fiber with a Gaussian function refractive index profile becomes a graded-index fiber. Graded-index-fibers have also been reported as mode-field adaptors for low coupling loss between SMFs and large mode area fibers [21].

$$n^2(r) = n_0^2 + \frac{a^2}{A^2}(n_1^2 - n_0^2)\exp(-\frac{r^2}{A^2}) \tag{3}$$

Where $A = 2\sqrt{Dt}$, is the expanded core diameter. D is the diffusion coefficient of the Germanium dopant activation at a certain temperature, a is the original fiber core diameter and t is the heating time.

We numerically simulate the signal transmission efficiency of a TEC fiber with different heating time. The refractive index profile of TEC fiber is describes as Equation (2), the temperature of flame is around 1700 ℃ and D is around $3.4\times10^{-14} m^2/s$. As shown in Fig.4, numerical simulation result indicates that the optimal heating time is 30 minutes. When heating time increases to 30 minutes, the monitored efficiencies of total power and LP01 mode power increase to a maximum of 93.3% and 80.1%, while the efficiency of LP02 mode power decreases to 12.4%.

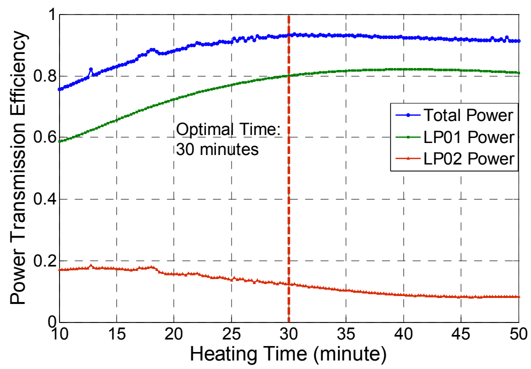


Figure 4. The monitor power transmission efficiency of a tapered thermally expanded core fiber with different heating time to a 25/250 DCF

In our fabrication process, the TEC fiber is produced by using a hydrogen/ oxygen flame. Fig.5 shows the TEC setup. The polymer coating of SMF-28 is stripped off with a length of around 3 cm, and the bare fiber is fixed between two clamps. A flame with a heating region of around 6mm is in the center of two clamps. The temperature of the flame is 1600℃-1700℃ by controlling the flow of hydrogen to 150mL/s and oxygen to 30 mL/s. As described in Fig.6, the measured expanded core diameters of TEC fibers under different heating time, 0 minutes, 10 minutes, 20 minutes, 30 minutes, 40 minutes are 10.7μm,19.8μm,28.4μm,35.2μm,40.5μm, respectively. Because the temperature distribution of flame in not uniform, the enlarged doped core will no longer be a circle when the heating time is over 40 minutes. Therefore, the optimal heating time is found to be around 30 minutes. And this is consistent with the simulation result.

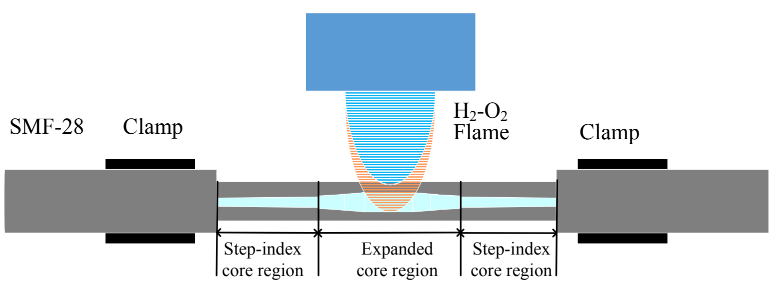
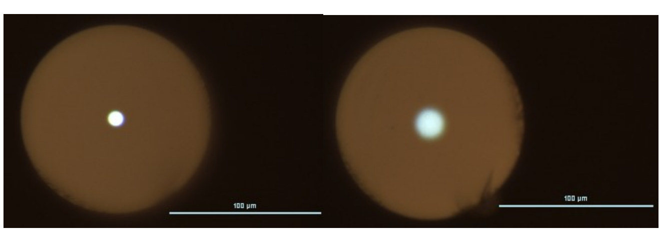
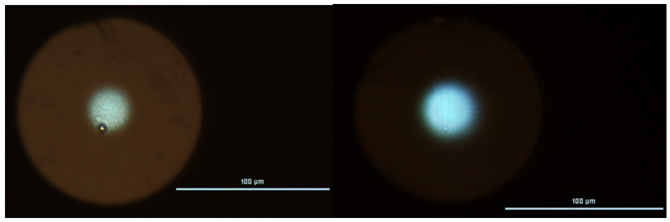


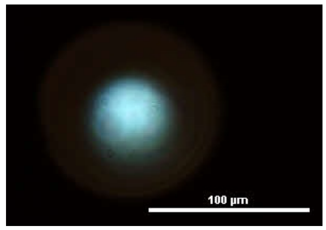
Figure 5. The TEC experiment setup, the SMF-28 fiber is heated by a hydrogen/ oxygen flame



(a) 0 minutes -10.7μm (b) 10 minutes-19.8μm



(c) 20 minutes-28.4μm (d) 30 minutes-35.2μm



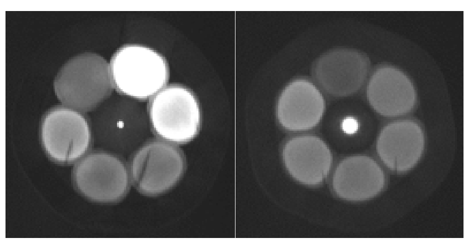
(e) 40 minutes-40.5μm

Figure 6. The microphotos of cleaved end-face of TEC fibers with different heating times

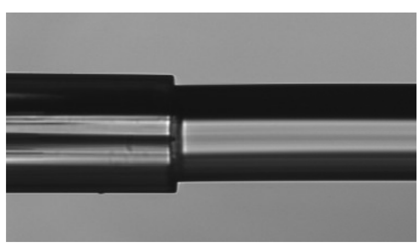
5 EXPERIMENT AND RESULT

The cross-section of the cleaved TFB with a standard SMF-28 as signal fiber is shown in Fig.7 (a). Compared with a TEC SMF-28 fiber in Fig.7 (b) which is in the same scale with (a), the mode-field diameter of signal fiber is obviously enlarged.

The cleaved fiber bundle is connected to a double clad deliver fiber (25/250), the side view of splicing the TFB and an output DCF is described in Fig.7. (c). In the splice-fusion process, 1064 nm seed laser is inserted into signal fiber to measure the transmission efficiency. With a standard SMF-28 signal fiber, the coupling efficiency is measured to be 54%. Compared with this measurement, the numerical simulation efficiency is lower. The possible reason is that the signal fiber is heated during the process of fusion and tapering.



(a) (b)



(c)

Figure 7. (a) Cross-sectional photograph of cleaved fiber bundle of a (6+1)×1 combiner with a standard signal fiber (SMF-28) (b) Cleaved end-face with a 30-minutes heated TEC signal fiber((a) and (b) are in the same scale) (c) Side view of fusion-splice between the TFB and an output DCF

By using a TEC SMF-28 fiber, the signal coupling efficiency increases significantly to 92.7%. Furthermore, the average signal coupling efficiency of our fabricated TEC combiners is around 93.3%.

The Fabricated combiner is then packaged in a metal box and connected to a water cooling system. Six multimode fibers are linked to 976nm pump laser diodes to measure their coupling efficiencies, and the measured transmission result of each port is shown in Table.1. The fabricated combiner has an average pump transmission efficiency of 96.7%. According to the splice loss equation (1), the 3%-5% fluctuation of pump coupling efficiencies is caused by the angular splicing misalignment.

Table 1 Port transmission efficiency of six multimode fibers measured at 976 nm wavelength.

Port#	1	2	3	4	5	6	Average
Transmission Efficiency	93.4%	95.5%	95.9%	99.8%	99.9%	95.9%	96.7%

To test the performance of our fabricated fiber combiner and to further demonstrate its practicability, a 5 m Yb-doped DCF with 25 μm core diameter and pump light absorption coefficient of 4.8 dB/m is spliced to the output deliver fiber. The configuration of this all-fiber amplifier testing system is shown in Fig.8. A 1064nm continuous-wave (CW) laser source is applied for the amplifier system as a seed source. Four ports of the multimode fibers are selected as testing channels and pumped with 976nm laser diodes. To strip out the redundant pump light, 0.5m of active DCF is removed the original polymer coating and recoated with a kind of high refractive index polymer [22]. A power meter is used to measure the output combined light power.

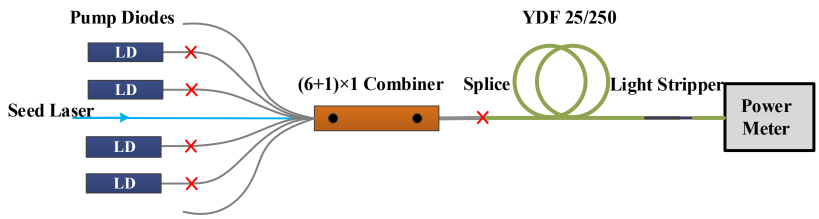


Figure 8. Experimental setup for testing the performance of fabricated combiner

The measured output laser power pumped with 976nm LD source is shown in Fig.9. The average conversion efficiency of launched pump power to signal power is 71.6%. And a maximum combined CW output power is achieved at 122.7W. Fig.10 illustrates the output light spectrum when input pump power increases. As can be seen, when input pump power is over than 110W, there is some redundant pump power and some amount of spectrally integrated ASE. Because the intensity difference of ASE and output power is more than 40 dB, it can be considered that ASE will not affect the performance of our amplifier system.

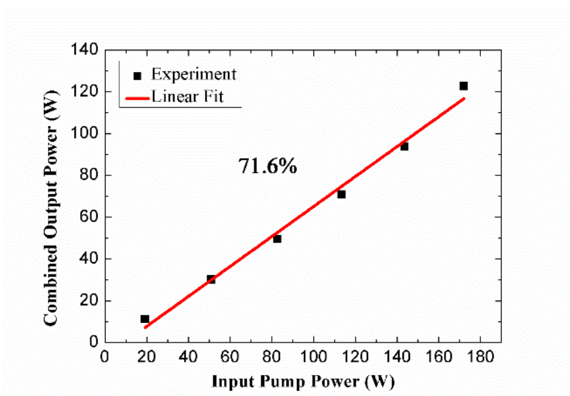


Figure 9. Slope efficiency of the amplifier system

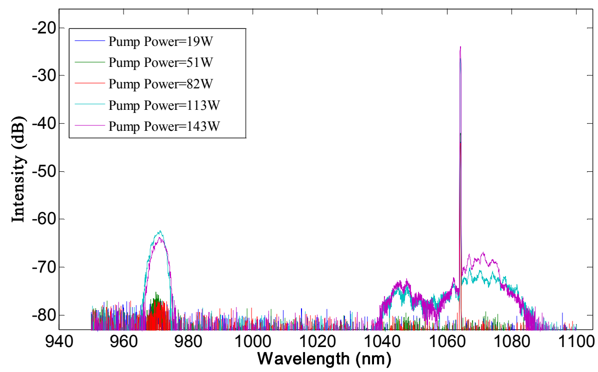


Figure 10. Output spectrum of the combined output laser

6 CONCLUSION

In conclusion, we have fabricated an all-fiber (6+1)×1 pump-signal combiner using a TEC SMF-28 fiber as signal feed-through fiber and six 105/125 multimode fibers as pump fibers. The output passive and connected active fiber are 25/250 DCFs. The average signal coupling efficiency of our fabricated TEC combiners is around 93.3%, which is much higher than the similar commercial combiners. The average pump coupling efficiency is 96.7%, and we believe that the pump coupling efficiency can be improved by further optimization of the splice loss from TFB to the delivery fiber. A maximum combined CW output power of 122.7W is demonstrated. The slope efficiency of the amplifier system is 71.6%.

ACKNOWLEDGEMENTS

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