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Fabrication of high-efficiency pump and signal combiner based on a thermally expanded core technique

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ABSTRACT

We have developed a high-efficiency $(6+1)\times 1$ pump–signal combiner for high power fiber lasers and amplifiers based on a thermally expanded core technique. The thermally expanded core technique can control the dopant concentration of the signal fiber, which can realize mode field match between the mode field sizes of the signal fiber and the output fiber. Using a thermally expanded core method, signal coupling efficiency is increased from 51% to 94% at the wavelength of 1064 nm. And we experimentally demonstrate that the optimal heating time for our signal fiber is around 30 min at a temperature around 1500 °C. At the same time, the pump coupling efficiency ranges from 96% to 99% at 976 nm. The high-efficiency pump and signal combiner can be implemented in many fiber laser or amplifier architectures.

1. Introduction

Recently, fiber lasers and amplifiers have received great attention because of their ability to provide high wall-plug efficiency, easiness of cooling, high efficiency and excellent beam quality at high power levels [1,2]. For the realization of all-fiber integration eliminating free-space components, fiber laser requires fewer components and mechanical parts, making them quite robust, reliable, and compact [3–5]. A high power all-fiber high-efficiency signal and pump combiner is one of the key components for an integrated fiber laser or amplifier system. There are two main configurations of signal–pump combiners. One is an end-pump technique; pump and signal fibers are bundled and tapered. [6–8]. The other one manages to couple light from the side, is a promising approach, called a side-pump technique which is difficult in making the coupling structure with high proficiency and reliability [9–11].

A fused tapered fiber bundle which is widely applied in fiber lasers and amplifiers is probably the most popular and reliable pump combiner capable of handling several hundred watts of pump power [7]. A pump and signal combiner has a fiber bundle where the central fiber is a signal fiber. The traditional fabrication process can be divided into four steps, bundle, taper, cleave and splice [6]. However, tapering of the fiber bundle will reduce the mode field diameter (MFD) of the signal fiber. Hence, the tapered signal fiber and the output pigtail double-clad fiber (DCF) can lead to a large mismatch between the mode field diameters (MFD), leading to a high signal insertion loss as part of the signal light is leaked to the inner-clad of the DC fiber and high order modes are excited. The high signal insertion loss can limit the signal power and can also cause damage to the pump diodes [10]. High order modes will degrade the beam quality of the output light [4].

The method of a thermally expanded core (TEC) [12–18] technique for SMFs which was firstly studied by M.N. Mcland rich in 1988 [12] has been successfully used to improve the coupling efficiency between the small-core SMFs and the large mode field fibers [16–20]. In our experiment, the TEC technique was introduced to realize mode field adaptation between the tapered input signal fiber and the output DCF. In Ref. [21], Wu also proposed of this idea, but they only theoretically study the loss of signal and pump fiber in a $(N+1)\times 1$ combiner. In experiment, they measure the coupling efficiency by splicing a tapered 20/400 DCF to a 20/400 output fiber at 1550 nm.

In this paper, we simulate the signal insertion loss between the tapered input signal fiber and the output pigtail DC fiber. Next, based on the thermally expanded core technique, we expand the mode field diameter of the SMFs with different heating time. Then, we fabricate a $(6+1)\times 1$ pump–signal combiner with different thermally expanded core diameter fibers as signal fibers. At last, the signal and pump light coupling efficiency are measured. Experiment results show that the thermally expanded core technique can effectively improve the signal coupling efficiency from 51% to 94%. The high-efficiency pump and signal combiner can be implemented in many fiber laser or amplifier architectures.

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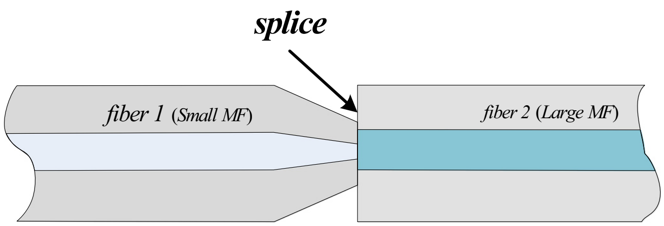

Fig. 1. Schematic splice point between the tapered input signal fiber and output fiber.

$$\varphi(r)=\begin{cases}\frac{w}{aV}\cdot\frac{J_0(\frac{r}{a}\cdot u)}{J_1(u)}, & r<a\\ \frac{u}{aV}\cdot\frac{K_0(\frac{r}{a}\cdot w)}{K_1(w)}, & r\ge a\end{cases} \quad (2)$$

where V is the normalized frequency, w and u are the transverse propagation constants, J_0, J_1 and K_0, K_1 are the zero-order and first-order Bessel and modified Bessel function in fiber, respectively.

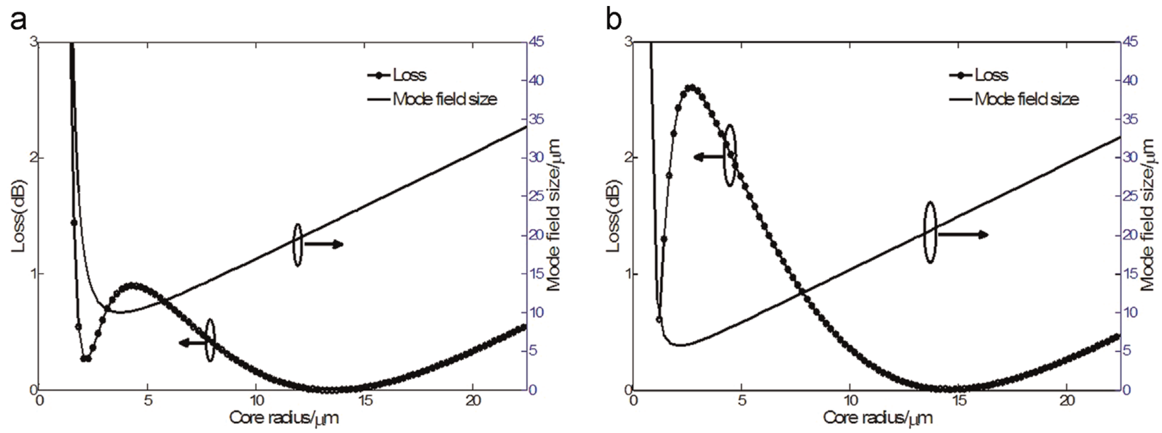

Fig. 2. MFD for fibers and mode-field mismatch loss between fibers with 25/250 μm (NA=0.06/0.46) and varied NAs and core diameters (A) NA=0.08 and (B) NA=0.14.

2. Theoretical analysis of signal loss in fused TFB

When two dissimilar fibers are fusion spliced together, a longitudinally varying transition region at the splice joint is produced. It is convenient to decompose the total splice loss at the splice joint to two different parts, the mode-field mismatch loss and the transition taper loss [22,23]. The transition taper loss can be neglected because the tapered fibers are adiabatic. The mode-field mismatch loss can be estimated based on the overlap integral of the field amplitudes of the guided modes using the following equation [8]:

$$\text{Loss}(dB) = -10\log_{10}\left[\iint \varphi_1(r,\theta)\cdot\varphi_2(r,\theta)\cdot r dr d\theta\right]^2 \quad (1)$$

where $\varphi_1(r,\theta)$ and $\varphi_2(r,\theta)$ are normalized field amplitudes of the guided modes for two fibers. Because the signal fiber is single mode fiber, we just consider the fundamental mode. According to the weakly guiding theory [24], the fundamental mode field in fibers can be expressed as

Table 1
The theoretical loss between some conventional input signal fibers and the output fiber with 25/250 MM (NA=0.06/0.46)s.

Type of fibers	Fiber #1	Fiber #2	Fiber #3
Parameters of the fibers in the form of core diameter (μm)/cladding diameter (μm)_NA	8/125_0.14	20/130_0.08	30/125_0.08
The core diameter of the tapered input signal fiber (μm)	5.33	13.16	20
The mode-field diameter of the tapered input signal fiber (μm)	5.95	12.4	16.92
Transfer efficiency (%)	54.86	86.32	96.36

To estimate the fundamental mode-field mismatch loss at the splice joint between the tapered input signal fiber and output fiber, the schematic splice point is shown in Fig. 1. Firstly the signal fiber is tapered with the pump fibers. The loss is determined using Eq. (1). Given the cladding diameter of the input signal and pump fiber is 125 μm and the output fiber is 25/250(NA 0.06/0.46), the taper ratio of the input fiber is 1.5 when the diameter of the tapered bundle is equal to that of the output fiber. For a fiber with a step index profile, the mode field profile of each guided mode can be computed analytically [7]. Fig. 2 shows how the mode field diameter (MFD) varies as a function of core size for different fixed values of refractive index, fixed NA. The MFD for fibers with different NAs and core diameter and the loss of the input signal fiber and the output fiber are also simulated, and the results are shown in Fig. 2. Fiber #1 has an 8-μm core diameter and a 0.14 NA, fiber #2 has a 20-μm core diameter and a 0.08 NA, and Fiber #3 has a 30-μm core diameter and a 0.08 NA. From Fig. 2, we can obtain the loss of between some conventional input signal fibers and the output fiber, as shown in Table 1. After the input signal fibers were tapered with the pump fibers, the core diameter of the fibers would be 5.33 μm, 13.16 μm and 20 μm, separately. The simulated results of the transfer efficiency between the tapered input fiber and the output fiber are 54.86%, 86.32%, and 96.36%. With the increase of the mode field diameters of the input fiber, the mode field would be match better and the loss would be lower. So in this paper, the thermally expanded core technique introduces to expand the mode field diameter of the input fibers.

3. Thermally expanded CORE technique

By heating a single mode fiber at high temperature (above 1500 °C), the germanium dopant spreads out from the core to the clad of fiber. As a result, the refractive index profile changes from step-index to a Gaussian function, which can be expressed as