Optical Fiber Technology 22 (2015) 90–94

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Numerical study on the propagation property of a single mode fiber beam combiner

Wenbo Liu, Jianqiu Cao *, Shaofeng Guo, Xiaojun Xu

College of Optoelectric Science and Engineering, National University of Defense Technology, Changsha 410073, PR China

ARTICLE INFO

Article history:
Received 19 October 2014
Revised 9 January 2015
Available online 14 February 2015

Keywords:
Fiber beam combiner
Fused taper bundle
Beam combining

ABSTRACT

We numerically investigate the propagation property of a 3×1 single mode fiber beam combiner in this paper. The evolvement of the optical field in the combiner is studied and the effects of the parameters such as the taper length, the taper ratio, the core diameter and numerical aperture of the output fiber on the performance of the combiner are analyzed. We find that the numerical aperture of the output fiber only has a negligible effect on the transfer efficiency of the combiner, while the taper length should be large enough to realize high efficiency. It is also suggested that the taper ratio and the core diameter of output fiber should be optimized for improving the performance of the combiner.

1. Introduction

High power fiber lasers (FL) have attracted much attention on account of its excellent performance on high output power, beam quality, overall efficiency, and flexibility [1,2]. One of the key components in a high power fiber laser system is the fiber beam combiner. The common type of fiber beam combiner is a fused tapered fiber bundle (TFB) spliced to an output fiber, used to combine the beams in the fiber bundle into the core of the output fiber [3,4]. Two key parameters are crucial to evaluate the properties of a fiber beam combiner, i.e., the transfer efficiency and brightness. The higher the transfer efficiency and brightness are, the better the combiner is. Nowadays, according to the mode number of the input beam, the fiber beam combiner could be divided into two types, i.e., multimode (MM) combiner and single mode (SM) combiner. MM combiner whose input beams are multimode, is traditionally used for combining the pump light generated from laser diode (LD) into the inner cladding of the double-cladding fibers [1,2]. Such a MM combiner is also called the pump light combiner. MM combiner is widely used in the high power fiber laser system [5,6]. However, the brightness of the input beams is low as they are multimode. Thus, the output brightness of MM combiner is also limited. Different from MM combiner, the input beams of SM combiner is single-mode, i.e., propagating mainly in the fundamental modes of the input fibers. Such a combiner is also called SM–MM combiner [7,8] which is generally used for beam combining of fiber lasers. In a high power fiber laser system, SM–MM combiner is not only used for combining cascaded pumping beams, but also used for combining high power fiber laser beams. The most important characteristic of SM combiners is the utmost preservation of beam brightness by the adiabatic taper [9,10]. As the input beam is single mode, SM combiner can achieve high brightness output [11,12]. In 2011, Shamir et al. produced a low mode TFB combiner with large mode-area (LMA) fibers. The low mode TFB combiner can be considered, not so strictly, as a SM combiner because of the high beam quality of its input beams. In their experiments, the brightness preservation of the combiner was demonstrated by comparing the experimental data with the theoretical predictions [11,13]. In spite of that, present studies were still limited on the specific design rules of the SM combiner and the propagation of the optical field in the SM combiner. More studies are still needed to fully understand the properties of SM combiner. In this paper, the effects of the structures of the taper and output fiber on the transfer efficiency of a 3×1 SM combiner are numerically investigated. The pertinent results will provide potential guidance for designing the SM combiner.

2. Simulation of the single-mode TFB combiner

The structure of the 3×1 single-mode TFB combiner we analysis is shown in Fig. 1. Three fibers are correspond to close-packed configurations, and then slowly fused and tapered with an external heat source, after the tapering process the fiber bundle is cleaved at the taper's waist and spliced to the output fiber. Because of the complicated wave-guide structure of the combiner, it's difficult to analytically study the optical field propagation along the combiner. Therefore, we numerically study the propagation of

---

* Corresponding author. Fax: +86 73184514127.
E-mail address: jq_cao@126.com (J. Cao).

http://dx.doi.org/10.1016/j.yofte.2015.01.020
1068-5200/© 2015 Elsevier Inc. All rights reserved.

the optical fields in the combiner. The numerical analysis method we adopted is the finite difference beam propagation method (FD-BPM) [14,15]. This method analyzes the optical field propagation in the wave-guide by numerically solving the Helmholtz equation, with the advantages of fast speed and high efficiency, and is widely used in the numerical studies of the fiber taper devices [11–13,16].

The model of the 3×1 TFB combiner is shown in Fig. 2. We assume that three fiber claddings are arranged in contact to each other, so the distance between two fiber cores is the diameter of fiber cladding. We also assume that the taper is linear and the end of the TFB is spliced to the core of the output fiber. As our attention is focused on the propagation process of optical field along the fiber core, we suppose that the cladding size is infinite, and thus, the influence of the cladding boundary on the optical field propagation is neglected. We also assume the input fibers are LMA fibers and the input optical field is in its fundamental mode. The parameters of the input fiber and optical field are given in Table 1. With this model, the optical field propagation in the SM combiner will be numerically investigated.

Table 1
Parameters of the input fiber and optical field.

λ (nm)	Core/Clad (μm)	NA	n_{core}
1064	15/130	0.10	1.46

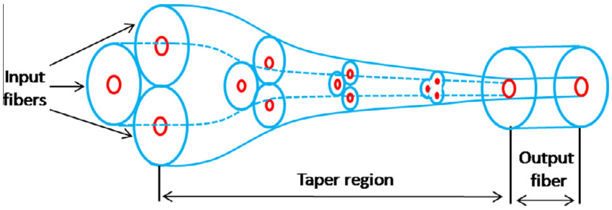

Fig. 1. Scheme of the 3×1 low mode TFB combiner.

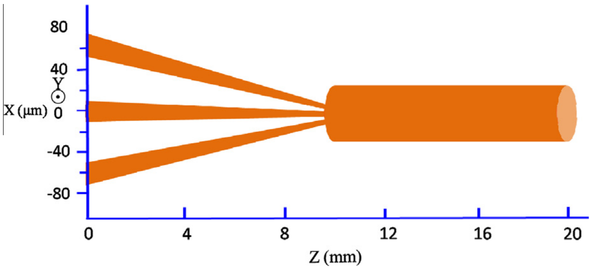

Fig. 2. Mathematical model of 3×1 FTB combiner.

3. Results and discussion

Initially we calculate the optical field propagation and the transfer efficiency in a typical TFB combiner. In this combiner, the taper length is 1 cm, and the taper ratio of TFB is 6:1. The core of the output fiber is 47-μm diameter with 0.12 numerical aperture (NA). The evolvement of the power distribution of optical field in TFB is given in Fig. 3.

As is shown in Fig. 3, the optical field preserves integrity well in the taper region without splitting, which implies that the adiabatic taper should be realized. Simultaneously, Fig. 3 also shows that the power distribution of optical field is changing gradually along the taper. It can be seen that when the propagation distance z is smaller than 6 mm ($z = 0$ is located at the input port of TFB, see Fig. 2), the power distribution is becoming more and more concentrated in its core along the TFB, and the mode field diameter (MFD) is reducing, correspondingly. This result is mainly caused by the reduction of the fiber core along the taper. However, with the further increment of the propagation distance ($z > 6$ mm), the power distribution is not further concentrated anymore. Instead, the optical field begins to spread around (see Fig. 3e–f), which induces the increment of the MFD of the optical field [12] and makes the power distribution more and more uniform (see Fig. 3f).

Fig. 4 gives the evolvement of the optical field in the output fiber. It can be found that the optical field is also changing along the propagation direction. The variation of the optical field in the output fiber is caused by the modes coupling. Considering that the output fiber is a multimode fiber, the input optical field which comes from the taper region, starts to couple into the intrinsic

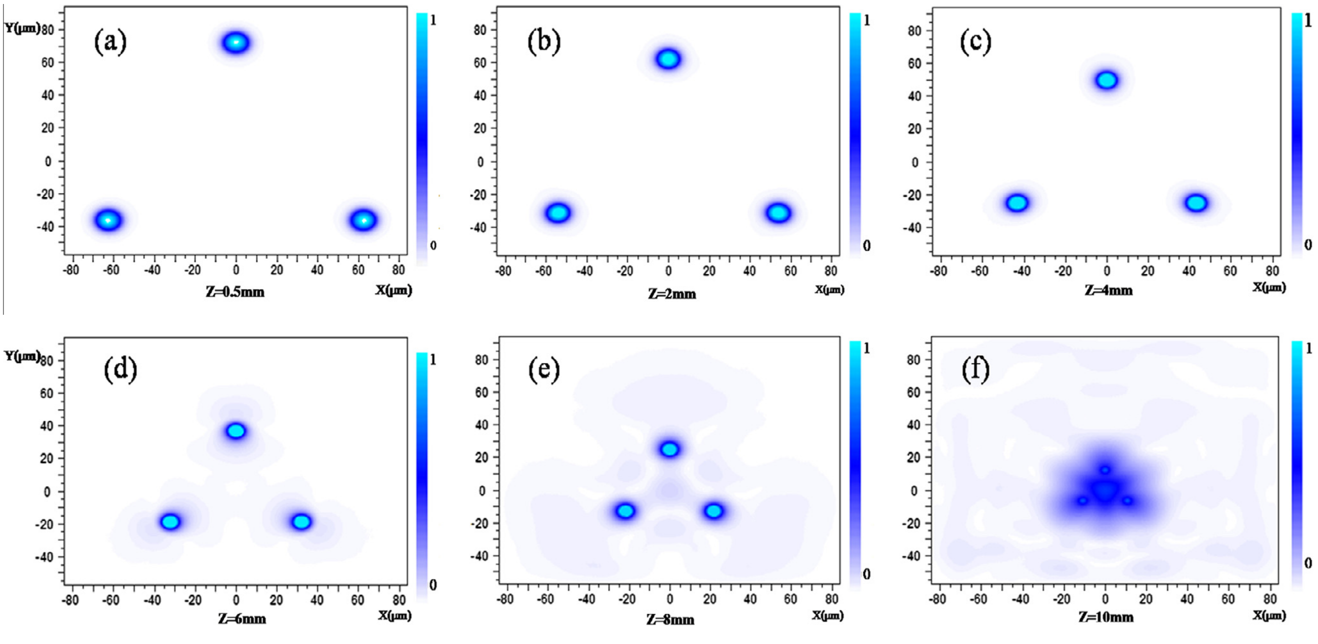

Fig. 3. Power distribution of the optical field along the TFB structure.