Optics and Laser Technology 107 (2018) 468–477

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Effect of the surrounding refractive index and fusion-depth on side-pump combiners

K. Madrazo de la Rosa [a,*], A. Martínez-Rios [a], T. Pórraz-Culebro [a], D. Toral-Acosta [a], L.F. Enriquez-Gomez [a,b], J.A. Guerrero-Viramontes [a,b]

[a] Centro de Investigaciones en Óptica A C, Loma del Bosque, 115, Col. Lomas del Campestre, 37150 León, Gto, Mexico
[b] TecNM/Instituto Tecnológico de Aguascalientes, Av. Adolfo López Mateos #1801 Ote, Fracc. Bona Gens, Aguascalientes, Ags. 20256, Mexico

ARTICLE INFO

Article history:
Received 3 November 2017
Received in revised form 24 April 2018
Accepted 4 June 2018
Available online 26 June 2018

Keywords:
Cladding pumping
Side coupler
Fusion depth
Refractive index

ABSTRACT

A study of the effect on the coupling efficiency due to surrounding refractive index and fusion depth variations in (1+1) side-pump combiners is presented. The external refractive index values used in the simulations are 1.0 and 1.35, which correspond to the refractive indexes of air and Teflon. The results showed that the coupling efficiency is not affected by a *Teflon-like* surrounding medium along the coupling zone as long as the tapers transition of the pump fiber is not too large to reduce the propagation angle below the critical angle of the receiving double clad fiber. Furthermore, modal simulations showed that the higher the fusion depth the faster the coupling of the pump modes.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

The great advances in the development of high power fiber lasers are largely due to the cladding pumping technology [1], where the double-clad fiber (DCF) waveguide structure plays a central role. Since the DCF cladding is readily accessible, pump light from high power multimode diode lasers can be efficiently coupled through the cladding. The methods for coupling the light into a DCF can be divided into two main configurations: end-pumping and side-pumping. Both methods can be implemented by bulk optical systems [2,3], or all-fiber arrangements [4,5]. However, side pumping configurations [6–10] have proved to be more advantageous, since the ends of the DCF are free to connect to other fiber components. In addition, it is possible to distribute the pump along the fiber length, so that the thermal management is more efficient and there are not overheating points on the DCF [11]. Additional techniques used for side-pumping, include *V* groove side-coupling technique [12], angle- polished method [13], embedded-mirror-method [14], micro prism side-coupling method [15], diffraction-grating method [16], and others. One of the preferred methods for efficient side-pumping is an all-fiber arrangement first proposed by Gapontsev [6], where the pump fiber is directly fused laterally with the cladding of the DCF. In order to enhance the coupling of the pump light into the DCF, the pump fiber is tapered prior to the lateral fusion. In fact, the characteristics of the tapered pump fiber are crucial for obtaining a good coupling. For example, simple geometrical considerations of ray propagation through couplers show that each time a ray hits the interface with the external medium at the tapers transition, the propagation angle reduces by two times the tapers angle.

Most of the published works on pump coupling technology focus on the fabrication process, which in general are variations from the original proposal from Gapontsev [6]. In Ref. [7] a side pump coupler which uses a heat shrinkable Teflon tube to keep in contact the pump and the double-clad fibers is presented. However, Teflon or a polymer with similar low refractive index also can be used for protecting or packaging the coupling zone. It is clear that protecting the coupler with a polymer may simplify the heat management; otherwise, as in the case of an air external medium, the coupler should be protected to avoid the contact with any surface and contamination by particles in the environment. If the coupler is coated with a low index polymer such as Teflon, the coupler can be put into a direct contact with a heat sink, which may increase its power handling capability.

In this work, the effect of the immersion of the coupling zone of a (1+1) side-pump combiner into a low-index surrounding medium like Teflon and air is analyzed and compared. First, a simple geometrical analysis is realized in order to outline some of the effects attributable to the tapers geometry and the refractive index of the surrounding medium. Then, the subsequent analysis and simulation is performed by using the commercial software Photon

* Corresponding author.
E-mail address: kmadrazo@cio.mx (K. Madrazo de la Rosa).

https://doi.org/10.1016/j.optlastec.2018.06.002
0030-3992/© 2018 Elsevier Ltd. All rights reserved.

Design, where variations on the fusion depth [17] between the two fibers are also considered. The main results of this simulation are that Teflon does not affect the coupling efficiency, and the use of a higher fusion depth implies that the necessary coupling length can be shorter.

2. Operation principle

Fig. 1 shows a schematic diagram of the (1+1) pump side coupler, where the pump light from a pigtailed diode laser is coupled into the DCF cladding from the side. In order to enhance the coupling, the pumping MMF is spliced to a section of coreless fiber (CF), which is tapered and fused laterally with the DCF cladding [6]. Despite the coupling of the pump light is realized through the CF section, from now we will refer to the side coupling fiber structure simply as pump MMF. Among several factors that affect the performance of the side coupler, the degree of contact between the fused fibers, determined by the fusion length L and fusion depth, has the biggest impact over the coupling efficiency. The employed fibers (MMF, CF, DCF) in the fabrication have the following characteristics,

MMF: 105/125 μm (core/cladding diameter) and 0.22 NA

CF: 125 μm core diameter

DCF: 10/125/245 μm (core/first cladding/second cladding) and 0.46 NA.

For the configuration of Fig. 1 it is critical to know the minimum coupling length that can be used in order to minimize losses. The minimum coupling length is the necessary length to ensure that the fundamental mode (propagating collinear with fiber axis) of the MMF cross towards the DFC. In other words, the experimental pump taper must be larger than the minimum coupling length to ensure a high coupling efficiency. The theoretical analysis considers two cases, in the first case the side-coupler is immersed in air, while in the second case the side-coupler is immersed in Teflon. On the other hand, the effects of varying the fusion depth between the MMF and the DCF over the coupling length L (see Fig. 1) are analyzed in order to investigate how the coupling efficiency is affected. The simulations were made in the software Photon Design, while a simple geometrical analysis (see Fig. 2) give us a practical simple rule for selecting the correct design of the pump taper for the analysis and practical implementation.

The coupling analysis of the side coupler started using the optimum ratio between the transversal section of the MMF and the minimum transversal section of the taper (waist of the taper). This ratio should be in the range 0.01–0.7 [3], and the preferred value is around 0.1. In our case, we used the preferred value of 0.1. The area of the MMF at the beginning of the taper is $A_{MM} = \pi\,(62.5\,\mu\text{m})^2$, and the optimum area of the waist was determined from: $A_{MM} = \pi\,(62.5\,\mu\text{m})^2\,(0.1) \Rightarrow D_{waist} = 10.5\,\mu\text{m}$. Hence, the optimum taper waist diameter is 10.5 μm, and this value was used for the experimental design of the pump taper.

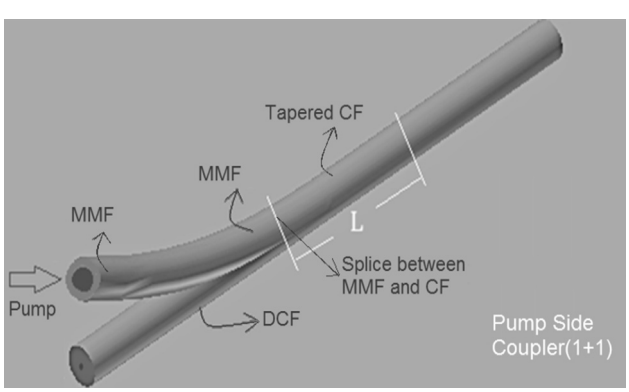

Fig. 1. Sketch of the side-pump coupler. A MMF is spliced to a CF, which is adiabatically tapered and finally laterally fused to the DCF.

Additionally, the critical angle of the receiving DCF represents the minimum quota for the permissible propagating angles. In order to determine this critical angle, it was used the following relation between the refractive indexes of the core (n_1)and the first cladding(n_2).

$$\theta_c^{DCF} = sin^{-1}\left(\frac{n_2}{n_1}\right) = sin^{-1}\left(\frac{1.3799}{1.4515}\right) = 71.93^\circ$$

where n_1 = 1.4515 (at λ = 915 nm) was obtained from the Sellmeier equation, whereas n_2 = 1.3799 was calculated from n_1 and the nominal NA of this fiber.

Fig. 2 shows the idealized 1D-geometry of the side-pump coupler, where it is assumed that the down-taper transition of the CF section starts at the joint with the MMF from the pigtailed pump diode. This idealized geometry from the real side coupler was used for tracing the paths of two different meridional extreme rays, where the thick and the thin lines correspond to a fundamental and a higher order mode rays launched into the MMF, respectively. The second of these traces stands for a caustic ray that propagates inside the tapered MMF before reaching the coupling structure, likewise, it can also represents any other higher order mode ray propagating within the limit case θ_c^{mm} (critical angle) of the MMF. In this case, after each reflection in the transition of the tapered section, the γ angle subtended by this ray with respect to the vertical, is reduced (see inset in Fig. 2) according to $\gamma \rightarrow \gamma - 2n\beta$ (i.e. $\gamma = \theta_c^{mm} - 2\beta$ when $z = z_1$); here, n represents the number of reflections occurring at the upper part only, and β is the taper angle. In a similar way, any fundamental mode ray represented by the thick line, also enters to the structure, here, the trace shows a single reflection at the transition of the tapered section, and the corresponding reduction in the propagation angle is given as $\gamma \rightarrow \gamma - 2\beta$ (in particular $\gamma = 90^\circ - 2\beta$). Is worth noticing that this fundamental mode ray, is the limit case of any higher order mode ray with increasing values of its corresponding γ angle, thus, a ray trace analysis applied to these extreme rays, accounts for all the meridional pump rays. A proper taper transition angle, ensures that after the last reflection in the taper transition and a posterior departure from the coupling structure, the γ angle of any of these rays will present a total value reduction that satisfy the acceptance conditions imposed by $\theta_c^{DC} = 71.93^\circ$, which, is the critical angle of the DC fiber. No further change is expected on the propagation angle of any ray reflected along the waist of the tapered MMF, that is, after the last reflection in the transition γ remains unchanged. In this way, if a ray exits from the coupling structure with a corresponding angle $\gamma > 71.93^\circ$, it will become bounded into the DCF.

Based on the foregoing considerations, for the design of the coupling structure the following facts were considered:

(i) In practice, the taper angle is usually small ($\beta \sim 1^\circ$), which produces fundamental mode rays that have the first reflection (at the taper transition) at a given z-length, where the higher order mode rays have already accumulated several reflections.

(ii) As a consequence, the condition $\gamma = 90^\circ - 2\beta > \theta_c^{DC} = 71.93^\circ$ is easily satisfied by the fundamental rays.

(iii) iii) For the higher order mode rays (especially those which come from the MMF with a propagation angle close to θ_c^{mm}), it is necessary to avoid a significant reduction of γ after n consecutive reflections. In this way, all these rays which after a last reflection on the taper transition leave the coupling structure with an angle according to $\gamma = \theta_c^{mm} - 2n\beta > 71.93^\circ$, will be coupled into the DCF.

Download English Version:

https://daneshyari.com/en/article/7128432

Download Persian Version:

https://daneshyari.com/article/7128432

Daneshyari.com