Modeling and optimization of multimode fused fiber combiners

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ABSTRACT

An effective method to predict the performance of multimode fused fiber combiners is presented. The realization of high power devices is strongly affected by the specific application, for instance whether used in fiber or in direct-diode lasers, and thus usually requires costly and time-consuming trial-and-error procedures. The proposed approach, which is based on ray tracing and statistical analysis, allows analyzing a-priori the impact of fiber dimensions, combiner geometry, glass material properties and laser beam quality on the coupling efficiency, therefore reducing the fabrication runs. Examples of application to 7-to-1 and 19-to-1 combiners are given and compared with experimental results.

Keywords: Pump combiner, fiber fused combiner, fiber laser, direct diode laser, ray tracing

1. INTRODUCTION

Fused fiber combiners are essential components for the realization of alignment-free, compact and robust all-fiber systems for communication, industrial material processing, medicine and sensing.[1–4] In particular, in high power fiber lasers and direct diode lasers, combiners are used to scale up the power by merging the output of several lower power sources[5,6] and this poses stringent requirements on the coupling efficiency and on the acceptable beam quality degradation. Indeed, the necessity of high transmission is not only to reduce power waste, but also to prevent local overheating that may cause the premature aging of the component or even lead to catastrophic failures. Different systems, however, have peculiar requirements and there is not the equivalent of the “one-size-fits-all” combiner, so its design and fabrication must be properly tailored according to the very specific application.

The usual path to optimize combiner performance is by trial-and-error methods, but this is costly and time-consuming; moreover, care must be taken in their characterizations since measurements are usually affected by working conditions, such as the beam emission characteristic of the laser source used during the tests.[7] To overcome these drawbacks, it is of great importance to have a tool to predict the efficiency of combiners before manufacturing, thus allowing the fabrication of high performance devices with reduced experimental optimization costs. The golden standard in combiner design is the “brightness conservation”,[7,8] which gives a theoretical lossless criterion. However, the “brightness conservation” only provides a general condition for proper combiner design and many other conditions must be met in actual fabrication in order to optimize the device; so other tools are needed to compare and choose among the possible options.

In this paper, an effective method to model and optimize multimode fiber fused combiners is proposed. The method is based on statistical analysis applied to ray tracing simulations that take into account the combiner design different parameters, such as fiber types, geometries, glass material properties and input beam quality. The proposed approach is then used to design two types of combiner: a 19-to-1 combiner used to realize a low-brightness direct diode laser system and a 7-to-1 combiner targeted for fiber laser system. Finally, experimental results are given and compared with the predictions.

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Components and Packaging for Laser Systems II, edited by Alexei L. Glebov, Paul O. Leisher, Proc. of SPIE Vol. 9730, 97300N · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2211345

2. COMBINER MODELING AND RAY TRACING ALGORITHM

Fused-fiber combiners come in different varieties, depending on the application requirements and fabrication techniques: for example, with or without feedthrough fiber, for side- or end- coupling, and with confining tube or not.

For large number of input fibers (for instance, 7 or more), the typical structure is that of a bundle: several fibers are packed in a glass capillary tube and are tapered down all together; then the bundle is spliced to a delivery fiber and the component is fixed in proper housing with low-index polymer.[9] Input fibers, especially for high power applications as targeted in this paper, are multimode, with the possible exception of the feedthrough fiber when present. This is the configuration considered in the following examples.

2.1 Combiner model

High power multimode combiners are made of input fibers with core size far larger than the beam wavelength (typically $> 100\,\mu\text{m}$ core, while the wavelength is around $800 - 900\,\text{nm}$ for devices used as pump combiners for Tm or Yb-doped fiber lasers), so ray tracing can be used to simulate light propagation within the fibers forming the bundle. Combiners, however, present also air gaps between the input fibers due to their cylindrical shape; as the bundle is tapered down to form the actual body of the combiner, the size of these gaps decreases and becomes in the order of the light wavelength. Wave optics suggests that light can be easily coupled into adjacent fibers across these thin air voids, while ray optics does not hold in this situation. Indeed, the critical angle of glass-air interface is about 43°, so a taper ratio higher than 4.9 is needed for rays to escape from a NA $= 0.22$ fiber and go into an adjacent fiber through an air gap. This is not adequately describing the actual situation; in order to continue using ray optics, it is usually assumed that the fiber bundle is so fused that all voids are totally filled with fiber cladding material (Fig. 1). Neglecting the contribution of confinement from air voids provides a worst case for estimating the transmission efficiency of ideal combiner (i.e., not considering deformation of fiber cores, scattering due to imperfections, etc.).

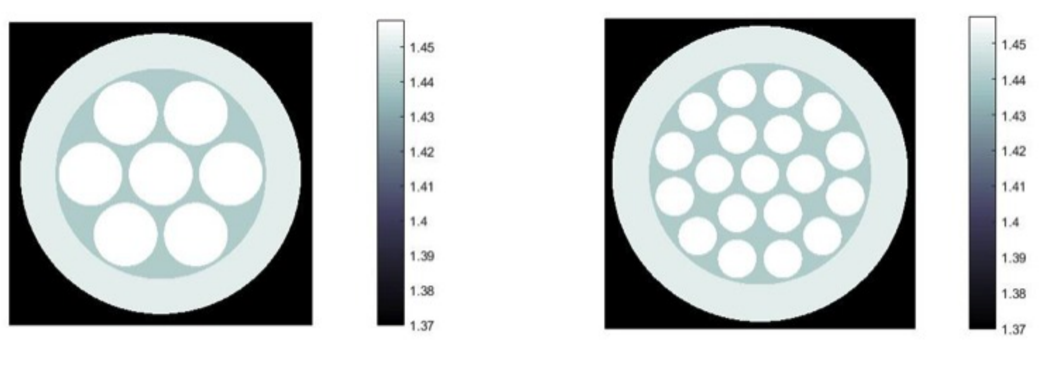

Figure 1. The cross section of a 7-to-1 (left) and a 19-to-1 (right) multimode fiber fused combiner model. The refractive index is indicated in the gray-scale bar.

Rays in the taper section (Fig. 2) can travel in four mediums: 1) fiber cores; 2) glass capillary tube surrounding the fibers; 3) fiber cladding filling the gaps between fiber cores and capillary tube walls; 4) optical resin outside the tube. Then, there is the output delivery fiber and only the rays that are able to be guided by the output fiber have to be taken into account in the evaluation of the combiner efficiency.

Assuming a linear taper shape for the fiber bundle, all the core/clad, clad/tube, tube/resin interfaces are conics with a common apex; so the problem now is to trace all the ray reflections and refractions occurring at these conical boundaries.

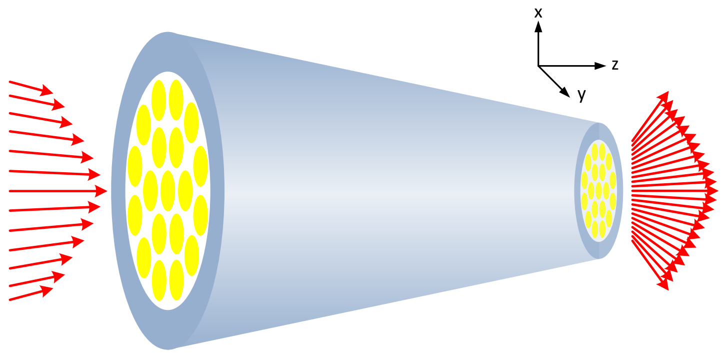

Figure 2. Schematic of rays input and output of the taper section of combiner.

2.2 Ray tracing algorithm

Numerical simulation based on a custom developed ray tracing algorithm were used to collect some statistical results by analyzing a large number of ray trajectories. In the combiner model described above, a bunch of rays are initiated in fiber cores at plane $z = 0$, with the position and direction of each ray being randomly generated: r, ϕ - the radial and angular position of ray origin; $\theta, \phi_{\mathrm{p}}$ - the angle of ray direction with respect to z-axis and x-axis, respectively. Optical power assigned to a ray P_{ray} is determined by the intensity distribution of input light (from laser diode), which is typically related to both of radial position and propagation direction. In this paper, for simplicity but not limited, super-Gaussian intensity distribution of order 20 is assumed.

The tracing of each ray is performed with the following procedure.

1. Specify the coordinates of ray origin and direction
2. Find the turning point where this ray reaches an interface between two media and reflection and/or refraction occur. A line can intersect with multiple conic surfaces, but a ray is considered to reflect/refract only at the closest interface.
3. Determine the direction and power of ray after reflection/refraction.
4. Update the ray origin and direction, trace the new ray segment through Step 2)-4).

   In this procedure a single ray can quickly turn into a huge number of ray branches due to reflections and refractions. To limit the computational requirements, any ray branch is terminated when meeting one of the following conditions: a) ray reaches the plane of the taper end, i.e. $z = L_{\mathrm{t}}$; b) ray escapes to into the resin layer; c) ray power goes below a threshold, thus becomes negligible.

Only rays terminated with condition a), located inside the effective area of output fiber (e.g. core in the case of a single-clad fiber, inner cladding in the case of a double-clad fiber) and having divergence no bigger than its numerical aperture (NA) must be taken into account in the evaluation of the combiner efficiency.

3. RESULTS

Being the most promising laser solutions for industrial material processing, high power direct diode and fiber lasers are rapidly gaining the largest part of the industrial laser market share. In direct diode lasers the output from a plurality of laser diodes is directly combined to scale the power up to the level required for the specific application. This approach leads to a high electrical-to-optical efficiency (at least compared with any other types of lasers) although typically with a lower beam quality. In particularly, using fused fiber combiners the beam quality is not particularly high, but appropriate for quite relevant applications such as plastic and thin metal welding or brazing.[6] For fiber lasers, combining of laser diode power is used to pump the active fiber, which then acts as a brightness converter and generates high quality beams suitable for metal cutting,[2] etc. In both cases multimode fused fiber combiners are the key component for the realization of monolithic systems. In this section, the design issues of combiners, such as taper ratio, taper length, capillary tube material and diode beam quality are analyzed using the simulation method previously described. As examples, two types of devices are analyzed:

- 19-to-1 combiner made with 105/125/0.22 input fibers and a 400/440/0.22 output fiber; this combiner, identified in the following as type I, can be used to deliver a multi-kilowatt power in a low-brightness direct diode laser system;
- 7-to-1 combiner made with 200/220/0.22 input fibers and a 20/400/0.06/0.46 double-clad output fiber; this combiner, identified in the following as type II, can be used to pump a fiber laser.

3.1 19-to-1 combiner for direct diode laser system

One of the key issues in designing a combiner based on the bundle structure is choosing the right capillary tube, which is added to hold the fibers together and easy the tapering process. In usual combiners the fiber bundle is tapered to have the capillary tube inner diameter matched with the effective diameter of the output fiber d_{out}, so the tapering ratio becomes $\mathrm{TR} = d_{\mathrm{tui}}/d_{\mathrm{out}}$, being d_{tui} the initial tube inner diameter, as in Fig. 3. However, light propagating through the taper section keeps diverging and might escape to the tube or even reach the resin. Reduction of this amount of power leakage can be effective to improve combiner efficiency. One possibility is to taper the glass bundle (including the glass tube) completely down to the effective area of output fiber, so $\mathrm{TR} = d_{\mathrm{tuo}}/d_{\mathrm{out}}$, being d_{tuo} the initial tube outer diameter; another possibility is to use tubes made of low-index glass, e.g. F-doped silica, to help light confinement.

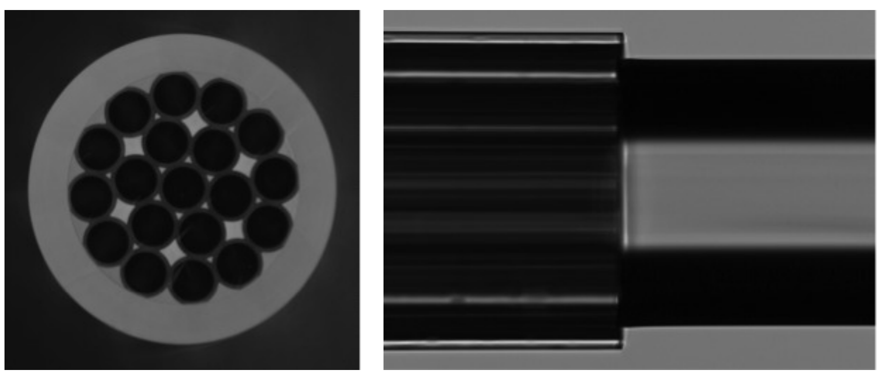

Figure 3. An example of 19-to-1 multimode combiner (type I): cross-cut with highlighted the capillary tube (left) and side view (right).

Fig. 4 shows the statistical analysis results of rays exiting the tapered bundle of the type I combiner with $\mathrm{TR} = d_{\mathrm{tui}}/d_{\mathrm{out}}$. As mentioned before, only light rays inside the effective area of output fiber and with a divergence smaller than the NA of output fiber can be coupled, i.e. $r < d_{\mathrm{out}}/2$ and $\mathrm{NA} < \mathrm{NA}_{\mathrm{out}}$. In the case of Fig. 4, it is clear that most of the power loss is due to NA out of the range. Therefore, it is even worse to have glass bundle completely tapered (e.g. from 97.5% to 83.7%), since r is reduced but worsening the NA.

On the other hand, if F-doped silica tube is used instead of fused silica, the efficiency of the same combiner in Fig. 4 increases a little, from 97.5% to 97.6%.

The impact of the taper length can also be analyzed. As shown in Fig. 5-left, for taper length L_{t} varying from 1 to 15 mm, the coupling efficiency of the combiner exhibits a rapid increase before 3 mm while is almost stable for longer taper values. The poor performance at small taper length is due to the fact that varying the fiber dimension at a too fast rate may cause rays angle changing too abruptly to be guided.

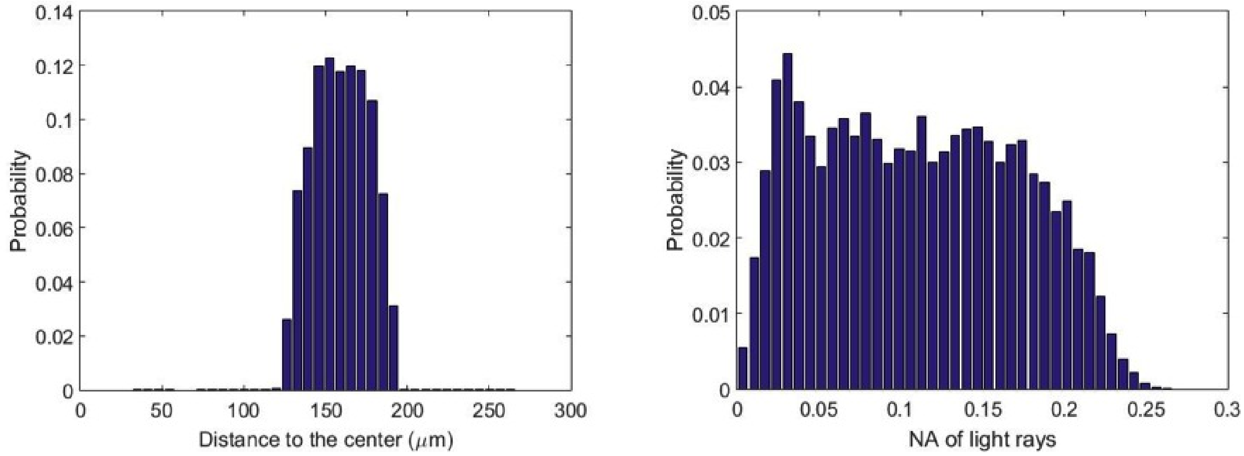

Figure 4. Statistical analysis of ray power distribution in the end section of the tapered bundle for type I combiner structure: distribution with the radial position (left) and the NA (right). The combiner has a taper length $L_{\mathrm{t}} = 10\,\mathrm{mm}$ and $\mathrm{TR} = d_{\mathrm{tui}}/d_{\mathrm{out}}$; feeding diode NA is 0.15.

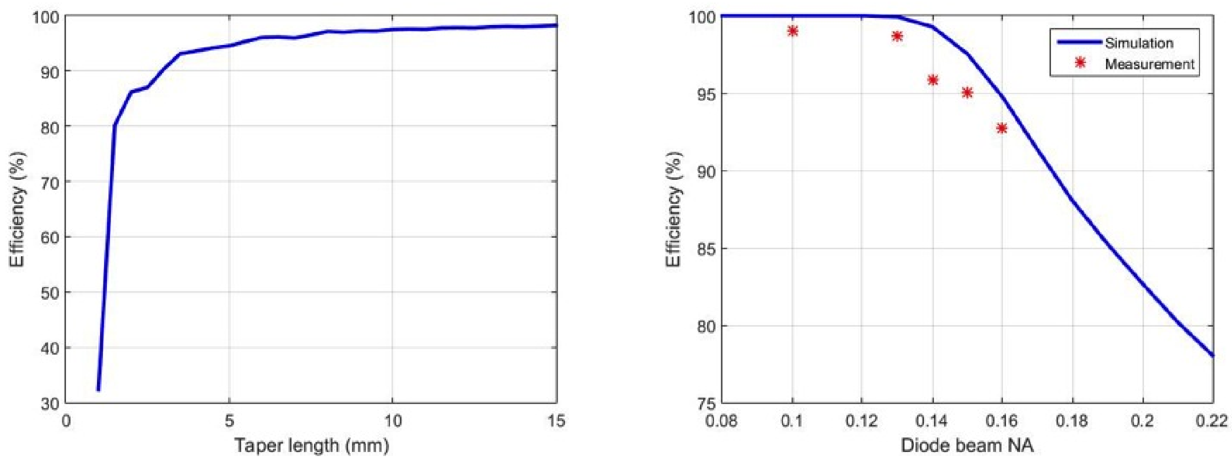

Figure 5. Dependence of coupling efficiency with the taper length (left) and the beam quality of feeding laser diode (right). The combiner is of type I, with $\mathrm{TR} = d_{\mathrm{tui}}/d_{\mathrm{out}}$. Diode NA is 0.15 in the left case and $L_{\mathrm{t}} = 10\,\mathrm{mm}$ in the right one.

Finally, the performance of a combiner are highly dependent on the beam quality of the input laser diode.[7] An example is reported in Fig. 5-right, together with experimental results obtained through efficiency measurements using different input laser diodes. Comparison between experiments and simulations shows an excellent agreement, therefore validating also the developed modeling approach.

3.2 7-to-1 pump combiner for fiber laser system

The same optimization procedure can also be applied to the design of 7-to-1 pump combiner for fiber laser pumping. Considering the fibers used in the above mentioned type II combiner, given the less stringent specifications for $\mathrm{NA}_{\mathrm{out}}$, the loss mainly comes from ray position out of range $r < d_{\mathrm{out}}/2$ (Fig. 6). Therefore, using the "complete taper" strategy, r can be reduced taking advantage of the NA margin (Fig. 7). Moreover, the combiner efficiency can be improved from 97.5% to 100%.

Moreover, using F-doped silica glass tube in this case also improves efficiency, from 97.5% to 99.7%.

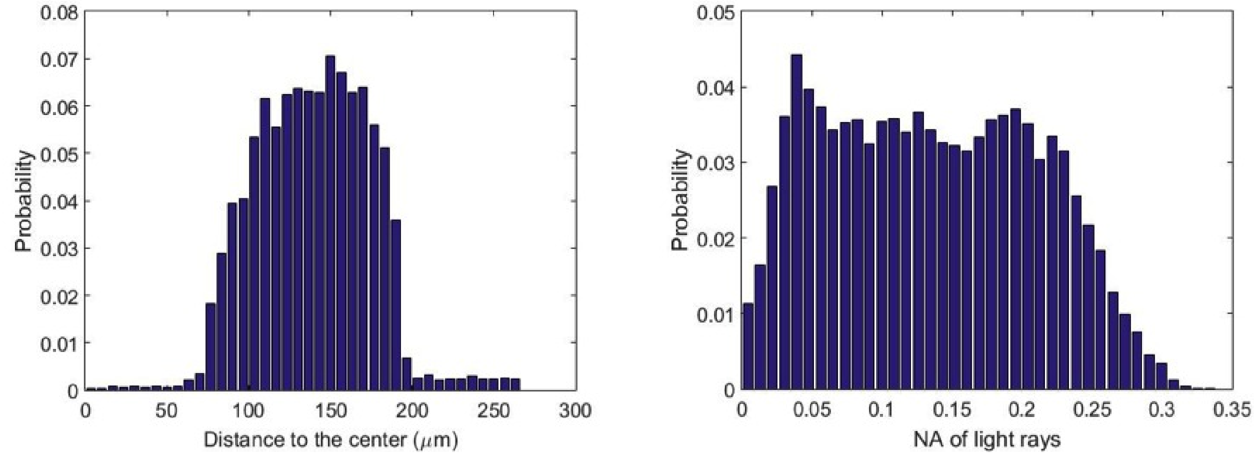

Figure 6. Statistical analysis of ray power in the end section of the tapered bundle: distribution with the radial position (left) and with the light NA (right). The combiner is of type II, with $L_{\mathrm{t}} = 10\,\mathrm{mm}$ and $\mathrm{TR} = d_{\mathrm{tui}}/d_{\mathrm{out}}$; diode NA is 0.18.

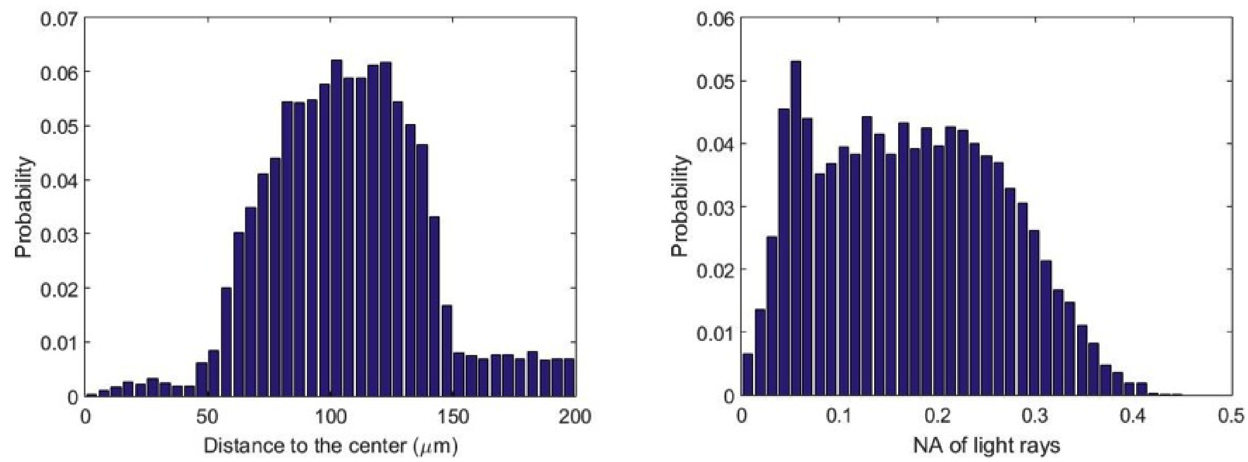

Figure 7. Simulation results of the combiner as in Fig. 6, but with a different taper ratio $\mathrm{TR} = d_{\mathrm{tuo}}/d_{\mathrm{out}}$.

4. CONCLUSIONS

An effective approach to model and evaluate multimode fiber fused combiner has been proposed. This approach is based on statistical analysis applied to ray tracing simulations and takes into account various design aspects of combiner. The glass bundle forming the combiner is modeled as a conic taper shape, with a glass capillary tube holding several fiber cores inside a uniform material having the cladding refractive index to allow using ray optics. This approximation worsen the predicted combiner performance since the presence of air voids can indeed help confine light; however, this is somehow counterbalanced by not considering other real issues during the combiner fabrication, such as deformation of the fibers, inclusion of dusts, and bad taper shape. The simulation tool has proved to provide quantitive indications that help saving time and costs in manufacturing, allowing, for instance, deciding in advance whether to use standard glass or F-doped glasses for the enclosing capillary tube, smaller or bigger tapering ratios, etc. Experimental measurements of combiner efficiency tested using different diodes demonstrate the validity of the simulations.

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