Monolithic all-glass pump combiner scheme for high-power fiber laser systems

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Abstract: We report on an integrated all-glass pump combiner for ytterbium-doped high power fiber lasers. The combining of multiple pump fibers with an active double clad fiber for high power amplification was successfully achieved by splicing them to a dichromatically coated planar convex lens. The measured coupling efficiency of such a combining scheme was typically in excess of 80%, with 86.5% achieved in maximum. Theoretical analysis is discussed in order to get optimized parameters and to consider the scaling of this type of coupler to higher average powers.

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (140.3510) Lasers, fiber; (140.3480) Lasers, diode-pumped

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1. Introduction

As the demand for integrated high power laser systems has increased, much research efforts have been focused on packaging and integration of laser systems into single units including pumping and amplifying. Recent investigations using fiber optics have led to various compact, reliable and efficient high power fiber laser systems for fundamental as well as industrial applications [1–4]. Especially, the development of the all fiber pumping concepts has been a key issue not only for scaling of the output power of fiber lasers but also for minimizing system size and cost of high power fiber laser systems. Thus, there were continuous efforts for integrating and combining lasing and pumping units in high power fiber laser systems. Especially for double clad fibers, the pump light has to access the pump core sidewise (side pumping) in order to get high coupling efficiency and to be able to use the fiber end facets for further signal delivery. This has been done through either side coupling methods which rely on polishing or peeling off the pump cladding, such as the V-groove side-coupling [5], the embedded-mirror [6] using an angle-polished fiber [7] or related capillary methods [8, 9]. These methods, however, suffer either from mechanical instability, low power handling capacity due to adhesives or reduced reliability potentially caused by partly damaged fibers. Other approaches used pump fibers that are fused and/or tapered to match the pump core while the signal light might be fed through this arrangement [10–12]. Furthermore, techniques that are currently used in commercial fiber laser systems are based on having the pump fibers in contact with the pump core along a certain length of the fiber and thus having a kind of side-coupling arrangement over a longer interaction length [13, 14]. These approaches have again the advantage of freely usable fiber end-facets. A drawback of these later methods is the limited design flexibility of the pump core area, which is to first order given by the sum of pump fiber and pump core areas and thus determines the absorption length.

In this study, we propose a miniaturized, monolithic all-glass pump combining scheme, which can be tailored to fit to the desired pump core geometry. It is based on the idea of surrounding the active double clad fiber by several pump fibers that are imaged to the pump core by a reflector. To achieve a monolithic device, all components are spliced in our case, where the reflector is given by the inner surface of a coated lens. The basic concept of reflecting the pump light to the pump core has been described recently [15]. Up to now, realizations of this scheme have been done by metallic hollow reflectors, where a hole in the center of that reflector separated the exiting laser beam from the fibers active core. One drawback of this method is that the active fiber needs to be polished at an angle for preventing back reflections to the amplifier, which makes the alignment of the hole relative to the emission cone difficult. In contrast, we present the realization by adopting a dichroically coated lens to achieve a high reflection and coupling efficiency for the pump light, while the laser light is transmitted. Splicing the lens to the fibers avoid angle polishing and critical alignment. Additionally, this lens serves as a protecting end-cap for high power or high energy generation. The whole system is also analyzed theoretically by ray-tracing (ZEMAX) and FEM (ANSYS). The simulations indicate potential for scaling to much higher power levels.

2. Device design and fabrication

The proposed structure consists of a dichromatically coated planar convex lens and a rare-earth doped double-clad fiber surrounded by multiple pump fibers. The schematic diagram of the proposed device is shown in Fig. 1. The side view of the system and the front view to the fiber end facets are depicted in Fig. 1 (a) and (b), respectively. The red dotted lines in Fig. 1 indicate the flow of pump light guided by pump fibers. The pump light, which exits from the pump fibers is imaged into the pump core of the actively-doped double clad fiber by reflection at the second, concave surface of the planar convex lens, which is coated for high reflectance at the pumping wavelength. The dichromatic coating of the lens makes it possible to propagate the amplified signal for further use, since the coating of the lens surface shows high transmittance at the lasing wavelength. It is noteworthy that firstly, the signal beam can expand by propagation in the lens and exit with lower intensity at the lens compared to the fiber turning this lens into a protective end-cap. Secondly, the dichromatical and geometrical arrangement protects the pump diodes from laser light to a high level. The proposed scheme could be applicable to almost all kinds of fiber laser systems, which utilize pump fiber and amplified fiber devices with free space output. To represent a typical Ytterbium-doped fiber laser or amplifier, the wavelength of 976nm for the pump source and ~1060nm for the signal source were adapted in this study.

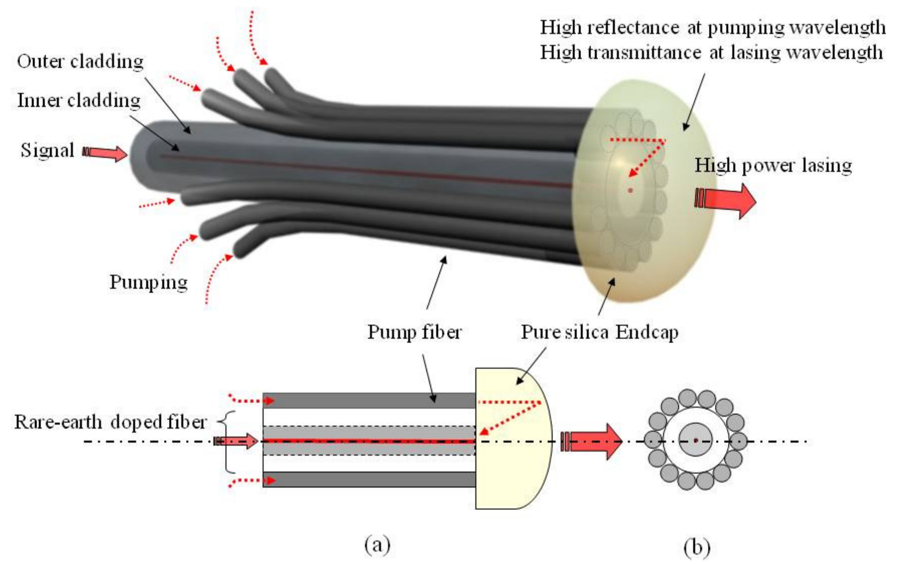

Fig. 1. Schematic diagram of the monolithic all-glass pump combiner; (a) Side view of the schematic diagram; (b) Front view image of the combined fiber end-facets.

Geometrical parameters for the system were theoretically confirmed and optimized by raytracing using the commercial package ZEMAX. The simulated results are shown in Fig. 2 and Fig. 3. Figure 2 shows the diameter of the image at the focal point of the convex lens that is used as a concave mirror, if a centered point source with given NA is used depending on the focal length of the lens. This gives a good approximation for the pump core diameter, which is required for 100% coupling efficiency. Conventional pump fibers typically have a NA in the range from 0.12 to 0.22. In the following, we used pump fibers having a NA of 0.12, a core diameter of 200µm and a cladding thickness of 10µm (whole diameter 220 µm). The active Yb-doped fiber is a double clad photonic crystal fiber (PCF) from Crystal Fibre™.

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The signal core diameter of the PCF is ~40µm. The outer clad diameter is 810 µm and the pump core diameter is 500µm. Similar fibers have been used for high average power fiber laser systems recently [16, 17]. For this set of parameters, the calculations shown in Fig. 2 suggest a focal length below 3.02mm. Figure 3 is a refinement of this calculation: The pump fibers are now separated radially and the dotted black contour lines show the size of the focal spot, whereas the red dotted contour lines show the corresponding NA of the imaging. The black solid line highlights the dimensions of the fiber we used and gives the boundary for the possible focal length of the lens (gray area). The lower limit (blue dotted line) is simply given by the outer diameter of the double clad fiber (radius 405 µm). The optimum focal length is 2.62 mm, which is given by the crossing of the limitation due to the pump core NA and its diameter to maximize the filling factor. The maximum usable filling factor (ratio of maximum incoupling to acceptance étendue) is 31.8%. As will be described in the following, the lens used in the experiment has a focal length of 2.5 mm due to production issues.

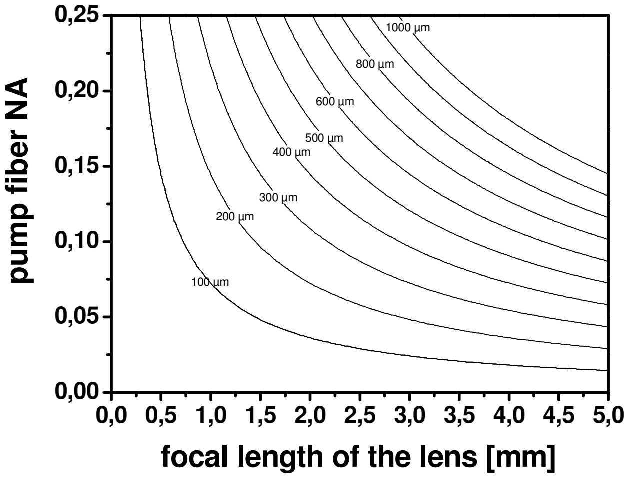

Fig. 2. Contour plot of the pump core diameter given in µm as a function of the NA of the pump fibers and the focal length of the lens (end-cap thickness) in order to get 100% coupling efficiency for a fiber in the center of the lens.

In order to accommodate lots of fibers for packaging, we adapted a ceramic holder having appropriable holes for each fiber of the designed structure. The ceramic holder could be simply removed after fixing the fibers by using a shrink tube. In order to splice it to the pure silica lens plane, the Yb-doped fiber and multiple pump fibers were cleaved, aligned and polished to obtain a single, smooth plane of fiber end facets. As a result, the height difference between end-facets of pump fibers and active fiber is below 1µm, which is small enough to splice the fiber bundle to the lens with high reproducibility of the splicing process. Microscope images of the packaged fibers and its side view image are shown in Fig. 4. Before splicing, the fiber bundle can be easily centered to the lens by feeding visible light through the pump fibers and observing the output of the pump core.

For the actual splicing process a modified CO2 laser splicing technique has been used. By varying the heating energy, which depends on the viscosity of the material and the concentration of impurities, we found the optimum splicing conditions for the proposed structure. Details of the joining process were described elsewhere [18]. After splicing, the shrink tube has been removed. Figure 5 shows images of a PCF-pump fiber bundle successfully spliced to a silica end-cap.

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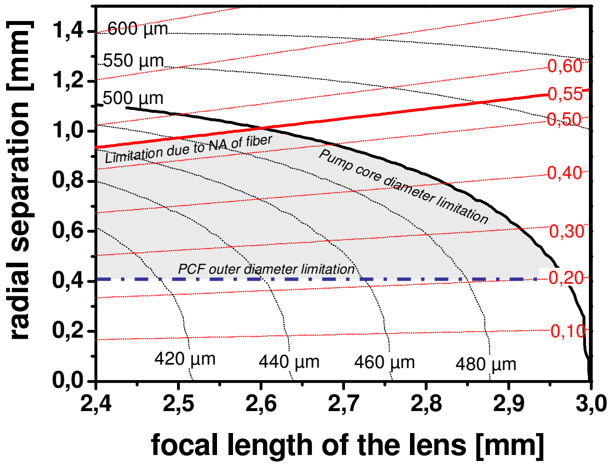

Fig. 3. The boundaries of the optimized parameter range in terms of the radial separation between pump fiber center and PCF center. Please see text for details.

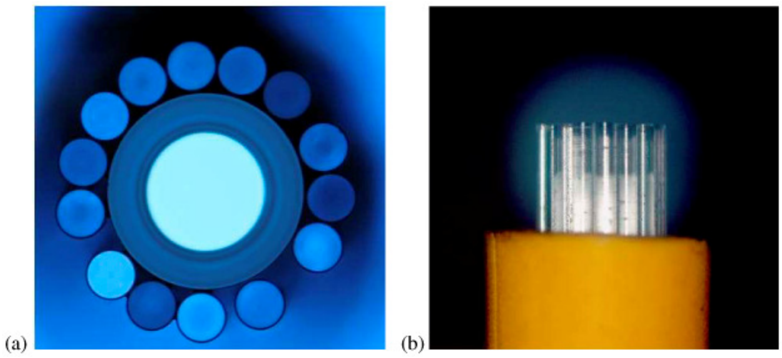

Fig. 4. Microscope images of the packaged fibers; (a) active fiber surrounded by multiple pump fibers; (b) side view image of the packaged fibers before removing the shrink tube.

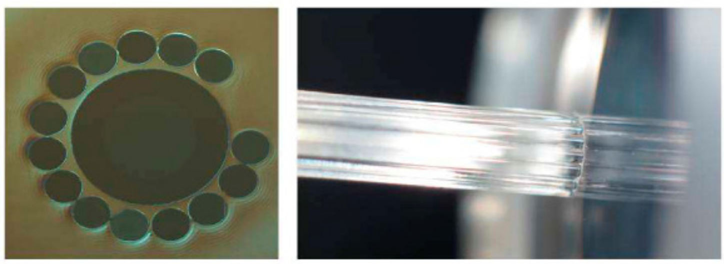

Fig. 5. Photograph of a fabricated all-glass pump combiner; spliced front view image (left) and spliced side view image (right).

The numbers of surrounding pump fibers N depend on the dimensions of the double clad fiber and can be approximated by $N = \pi / \arcsin(d_P / (d_P + d_{DC}))$, where d_P is the pump fiber diameter and d_{DC} is the diameter of the double clad fiber. For the 810µm diameter of the PCF used, a maximum of 14 pump fibers having a diameter of 220µm could be arranged circularly around the PCF. Note that the device can be directly applicable in high power fiber laser systems since we can adapt many pump fibers within the permissible diameter range. For the experimental measurement of the coupling efficiency, a system with 14 fibers has been

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fabricated with a dichroically coated planar convex lens from Asphericon™. The planar convex lens has the curvature radius of 5mm and the thickness of 2.5mm, which fits nicely to the design for the highest coupling efficiency. The dimensions are shown in Fig. 6 together with a ray-tracing simulation of the pump light coupling. These dimensions can of course be adapted according to the designed structure and purpose of the system.

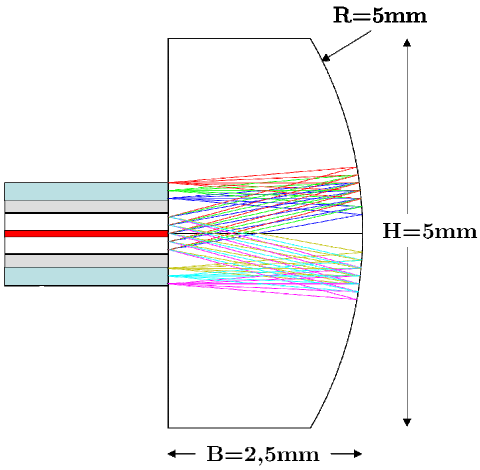

Fig. 6. Actual dimensions (R = radius, H = thickness, B = length) of the end-cap lens and raytracing of the pump light coupling.

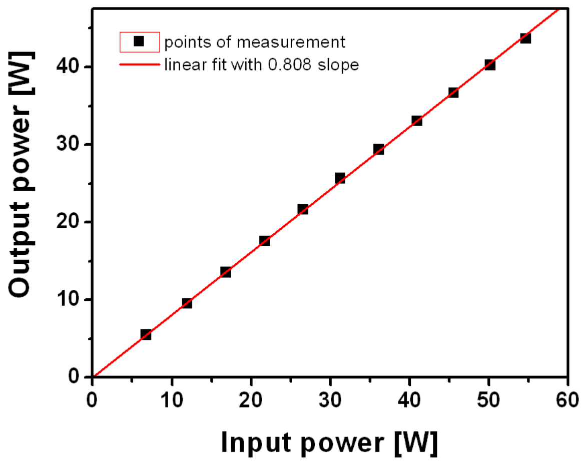

Fig. 7. Measured coupling power versus launched pump power.

3. Experiments and results

Optical properties of the device were investigated in terms of coupling efficiency and amplified output signal power along with launched pump power. In order to characterize the coupling efficiency of the devices, a passive PCF having exact the same structural parameters was tested in the beginning. Pump light was launched into each pump fiber channel and the power coupled to the pump core was measured by an optical power meter. Then, the coupling efficiency was calculated by comparing the incoming power before the end capped mirror with the output power after launching and passing the PCF (in this case, the lens was not spliced and could be removed). Five channels were selected as testing channels among 14 pump channels. For minimizing leakages of the pump light from the pump fibers, fiber

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pigtailed pump sources from IPG™ were utilized, which filled the available brightness of the pump fibers (200 µm, NA=0.12) by free space imaging. The geometry of the used coupler design suggests a NA of the incident light between 0.25 … 0.36 (see also Fig. 3), which we could measure at the exit of the PCF. Thus, the NA was maintained during propagation in the pump core. The central operating wavelength of the pump source was 976nm with a FWHM of 6nm and a maximum power of 20W. In this investigation, the pump power of each channel was adjusted in a range of 1W to 11W. The measured coupling efficiency of the device is shown in Fig. 7. The efficiency of pump power coupling into the 500µm pump core was above 80% up to a total power of 55W. It is noteworthy that it showed a very good linearity without thermal issues when increasing the launched pump power. In a fiber amplifier experiment using 15 m of Yb-doped PCF with a pump absorption of 1 dB/m, this coupler has been tested and a slope efficiency of 70% has been obtained. The power level of 25 W, however, was limited by the strong wavelength drift of the pump diodes, making the laser inefficient due to unabsorbed pump light at higher power levels.

4. Discussion

One of the limitations in observed efficiency has been the collapse length of the air-clad during the splicing process. The typical length of this collapse is 100µm after polishing. By further polishing down a fiber bundle to 50µm collapse length and butt-coupling it to an end-cap lens, we were able to increase the coupling efficiency to 81.6% and at 10µm collapse length, the coupling efficiency was 86.5%. During these experiments, other parameters have not been changed, meaning the fiber end-facet positions remained fixed and are of high surface quality due to the polishing process. For further improvements, it seems therefore necessary to include the collapse length in the design iterations discussed above. Nevertheless, it cannot be guaranteed that Fresnel reflections are avoided by this butt-coupling method, which is an additional reason for the lack of efficiency. Additional mechanisms for limiting efficiency are not yet investigated completely and are subject of ongoing work.

Additional considerations and experiments have been carried out to demonstrate further scaling possibilities. The coupling efficiency was measured as a function of the separation between the pump fiber and the double clad fiber. The result is shown in Fig. 8(a). At a center-to-center separation of 755 µm, which is close to the maximum possible as shown in Fig. 3, the efficiency dropped to 73%. At this position, the NA should be filled from 0.378 … 0.493, which was confirmed by the measured values of NA=0.376 … 0.488 at the fiber exit (95% power content). Again, a reason for the drop in efficiency is the collapse length, which is, of course, more critical if the fiber separation increases. It might also be possible that the guiding of the fiber at such high numerical apertures is less effective and leads to losses. Further investigations will be carried out in the near future. Nevertheless, this separation might be used to place more fibers around the PCF as shown in Fig. 8(b). There, 42 fibers with 220 µm diameter have been placed within the minimum and the maximum radii, where r_{min}=405µm and r_{max}=855µm. Currently diode technology allows for more than 100 W out of these fibers with a NA of 0.12 as used here. Thus, average power above the kW level might be possible by this approach.

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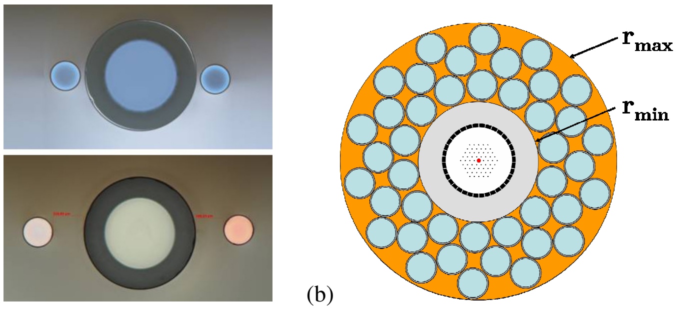
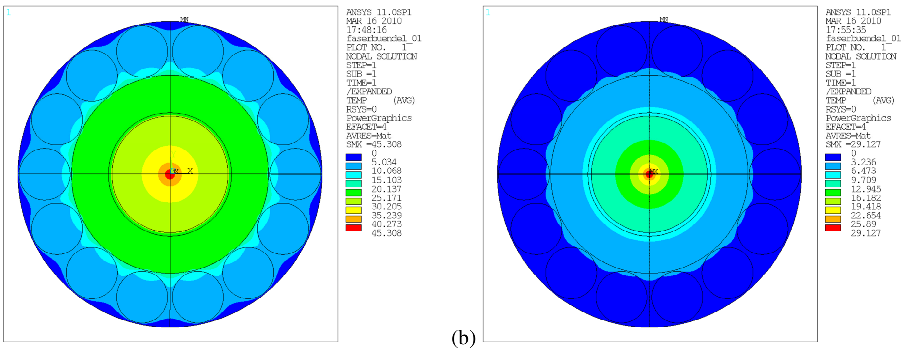


(a) (b)

Fig. 8. (a) Test arrangement of coupling efficiency for different pump fiber separations, (b) schematic drawing of the maximum distance of pump fiber positions given by the coupler design.

However, if such high power levels are aimed, the heat generation in the active core has to be considered even close to the end-cap. In this case, active cooling of the fiber device can be performed as has been shown in high power experiments before, where the end-cap was used as a supporting structure in a water-cooled fiber connector [16, 18]. For the device presented here, water cooling might be possible, because it would not influence any guiding mechanism. However, other cooling strategies might also be more applicable. To prove this statement, we performed an analysis by FEM using a two-dimensional (cut-view) model [19] of the fiber bundle. The whole bundle is assumed to be surrounded by a metallic sleeve as a heat sink. Five micrometer spacing is assumed between the PCF and the pump fibers, and between pump fiber and sleeve, respectively. A thermal load of 50 W/m (corresponding to ~500 W/m generated laser power) is applied onto the laser core of the PCF, while the sleeve is kept at constant temperature. For the filling between the fibers, different materials are considered: air (0.0243 W/m/K), and acrylic coating (0.3 W/m/K). The results of both materials are summarized in Fig. 9(a) and (b).



(a) (b)

Fig. 9. Temperature distribution in the fiber bundle. The embedding medium is air (a) or acrylate coating (b).

The maximum temperature in the fiber core is well below the allowable 100°C (i.e. $\Delta T<80K$) in both cases. The temperature gradient over the region of the pump fibers amounts to 20.7 K in the case of embedding in air. This value reduces to 4.4 K for a bundle embedded in acrylic. Though the difference in thermal conductivity of acrylic and air is more than a factor of ten the temperature gradient over the region of the pump fibers changes by a factor of five only because the thermal flux mainly concentrates inside the pump fibers as can be seen in Fig. 10.

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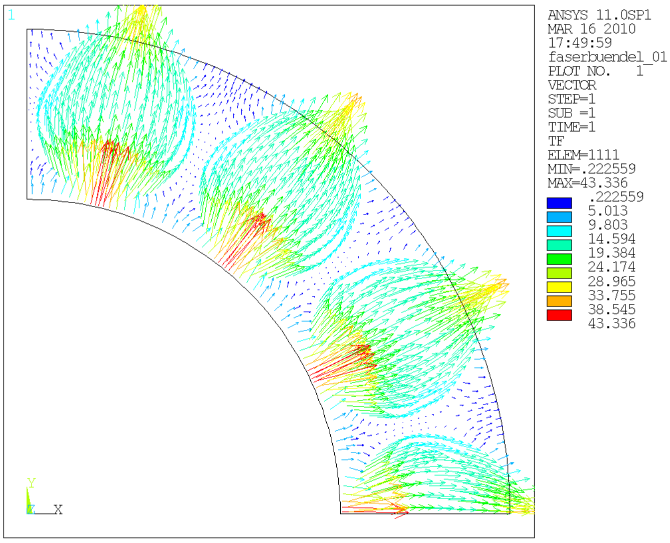

Fig. 10. Thermal flux distribution in a 90° segment of the outer region of a fiber bundle embedded in air.

Another consideration was the influence of the lens to the beam quality and/or collimation issues as well as surface damage issues if using high energy pulsed light: For the geometry presented here with a focal length of 2.5 mm and a single mode beam with NA~0.02, collimation is accompanied by a relatively large divergence, which can simply be compensated by placing a second collimation lens after the beam exit without any beam quality degradation. However, the beam expansion within the end-cap lens is low for the short length in the example discussed here. The beam expands by a factor of ~2.2 on the exit surface if a Gaussian beam out of the 40 µm core is assumed. Using typical damage threshold values specified for dichroic coatings of 10 J/cm^2 for 10 ns pulses, the device can handle energies of several µJ. Higher pulse energy in the range of ~100 µJ might be to achieved with longer focal length. Of course, if such long end-cap lenses are used, a complete redesign of the pump coupling is necessary and is not simply achieved by attaching the pump fibers to the outer cladding of the center double clad fiber.

Reflections of the laser light back to the pump fibers and diodes are greatly reduced due to the transmission of >99% through the lens. The curvature of the lens does not influence the spectral performance of the transmission in the region of the laser beam due to its small NA (incident angel ~0°). Up to the power levels tested in the amplifier experiment, no issues on back reflection to the laser core have been observed.

5. Conclusion

We realized a novel, compact all-glass pump combiner using a dichroically coated planar convex lens in combination with an Yb-doped fiber surrounded by multiple pump fibers. By combining amplifying and pumping units, a miniaturization of a high power fiber laser system was achieved. The device showed very good pump coupling in excess of 80% up to a total power of 55W without any signs of system instability due to thermal effects. A pump coupling efficiency of 86.5% has been measured by reducing the collapse length and butt-coupling of the imaging lens. The all-glass structure, assembled by laser splicing, makes the system stable, robust and suitable for high power operation with free space output, which is a typical requirement in short pulse fiber amplifier systems with a grating compressor. With the monolithic pump combining technologies, we confirmed that the proposed device has a potential application not only in kW range high power fiber lasers but also in compact photonic devices.

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