Highly-Integrated Signal and Pump Combiner in Chirally-Coupled-Core Fibers

Sven Hochheim, Eike Brockmüller, Peter Wessels, Michael Steinke, Joona Koponen, Tyson Lowder, Steffen Novotny, Jörg Neumann, and Dietmar Kracht

***Abstract*—Integrated fiber components enable compact and robust laser systems but are usually not available with specialty fibers. However, specialty fibers allow power scaling of fiber lasers and amplifiers with all advantages of these fiber designs. In this context, chirally-coupled-core fibers show promising properties for optical fiber components. In this paper, we present the development of a highly-integrated signal and pump combiner in chirally-core-fibers using a side-pumping technology. Combining up to four fiber-coupled pump diodes, a pump-light limited power handling of 600 W can be achieved with an efficiency of 78%. The combiner was tested in a side-pumped single-frequency all-fiber amplifier but can also be implemented in almost any fiber laser or amplifier.**

***Index Terms*—Specialty fiber, chirally-coupled-core fiber, signal and pump combiner.**

I. Introduction

A VARIETY of applications such as light detection and ranging (LIDAR), atom cooling or gravitational wave detectors require high optical output power at a narrowband laser linewidth [1]–[3]. The demand for compact, reliable and efficient monolithic high power laser systems has been increased in recent years [4], [5]. The efforts of all-fiber solutions expedite the development of integrated optical fiber-based components for almost all laser applications. Especially, in the next generation of gravitational wave detectors single-frequency and high-power laser sources have to fulfill special requirements with an excellent beam quality in a compact and reliable system [3], [6]. It has been shown that fiber amplifiers and especially all-fiber systems with integrated signal and pump combiners can be a suitable option to overcome current limitations [7].

Manuscript received March 23, 2021; revised July 7, 2021; accepted September 7, 2021. Date of publication September 13, 2021; date of current version November 16, 2021. This work was supported in part by the Max-Planck-Institute for Gravitational Physics, Hanover, Germany, and in part by the Deutsche Forschungsgemeinschaft, DFG, German Research Foundation, under Germany's Excellence Strategy - EXC 2123 QuantumFrontiers under Grant 390837967. *(Corresponding author: Sven Hochheim).*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2021.3111993.

Digital Object Identifier 10.1109/JLT.2021.3111993

The ultimate limitation of single-frequency fiber amplifiers is the nonlinear effect of stimulated Brillouin scattering (SBS). In general, to reduce the impact of such nonlinearities, the mode area of the fiber core is enlarged and special fiber types like photonic crystal fibers (PCF), photonic bandgap fibers (PBG), etc. have been developed and successfully tested [8], [9]. In this regard, the particular fiber concept of a chirally-coupled-core (3C) fiber has been specifically designed to enable single-mode operation with a large mode area core. The 3C-fiber consists of an all-solid fiber structure, whose signal core is additionally chirally surrounded by one or more satellite cores. Because of quasi-phase matching and the helical geometry, the higher order modes (HOM) are pulled out of the signal core, which enables a pure fundamental mode operation in the core [10]. Thereby, to overcome the limitation of SBS, the principal performance of 3C-fibers in single-frequency all-fiber amplifiers have already been proven [11].

For further power scaling of all-fiber lasers or amplifiers, a highly integrated signal and pump combiner is a key component. Fused tapered fiber (TFB) bundles are the most common type of fiber combiner [12], [13] and are based on the fiber end face pumping technique. The capability of handling several hundred watts of pump power makes a TFB practical for a variety of fiber applications [14]. However, a TFB consists of a tapered signal fiber and several tapered multi-mode fibers, where the numerical aperture (NA) of the pump light and the mode field diameter (MFD) of the signal light are, often, changed by the taper process. The necessary optical mode matching and the fusion splice to the output standard double-clad fiber lead to several drawbacks of the TFB architecture. On one hand, the flexibility in the choice of input fibers matching to the output DC fiber is reduced and on the other hand, a slight mismatch or misalignment degrades the beam quality significantly in conjunction with signal insertion loss. In the case of counter-pumped fiber lasers or amplifiers, the signal insertion loss (up to 10%) can couple into the pump diodes and damage them due to their insufficient isolation against amplified signal light. Specialty fibers can theoretically be used in a backward propagating TFB design, whereby they are practically not utilized due to the desired use of a standard LMA fiber in the high-power regime. In principle, the SBS threshold and the corresponding reachable output power of counter-pumped single-frequency fiber amplifiers can be increased compared to co-pumped systems significantly.

A more promising approach to overcome these problems is a side-pumping technology [15], where the coupling of the pump

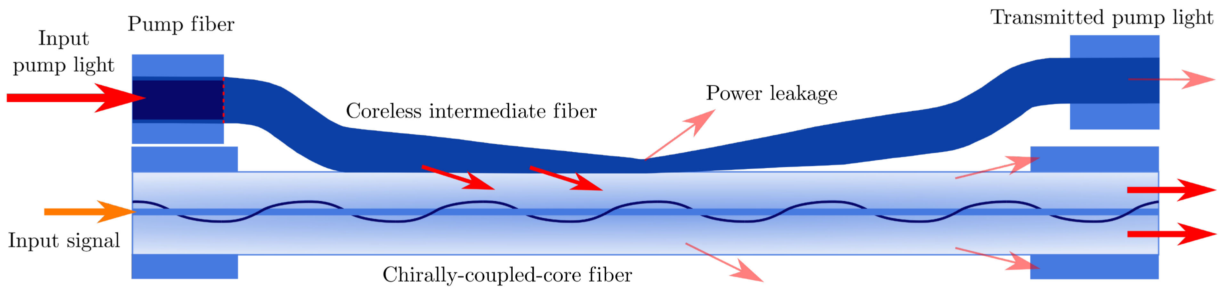

Fig. 1. Schematic side view of a side-pumped 3C-fiber including important ray paths. The pump fiber is spliced to a tapered coreless intermediate fiber, which enables an efficient pump light coupling to the 3C-fiber.

light can be achieved via the outermost cladding surface into the signal fiber. The key advantage of this technology is an uninterrupted core of the signal fiber, which is a significant advantage for the use of specialty fibers in this combiner architecture. However, micro-structured air holes such as used in PCFs collapse due to the manufacturing process, but all-solid designs such as 3C-fibers are not affected. Furthermore, the need for an additional fusion splice in conjunction with signal mode matching can be avoided.

For the first time, we report the development of a highly-integrated signal and pump combiner (SPC) in 3C-fibers combining up to 4 fiber-coupled multi-mode pump sources using side-pumping technology. The designed SPC was characterized to a tested maximum pump power of 600 W at efficiencies in the range of 75 to 80%, which is lower compared to commercial combiners for standard fibers. We found that the lower efficiency might be linked to specific aspects of the 3C fiber geometry as detailed below.

II. Optical Design of the 3C-Fiber Combiner

A schematic view of the side-pumped combiner consisting of a pump fiber (PF), a coreless intermediate fiber (IF) and a 3C-fiber is shown in Fig. 1. The incoming pump light was guided in the PF and propagates through the tapered portion of the IF. The IF was fusion spliced to the PF with a commercial filament splicing system and a hydrogen-oxygen micro-flame of a commercially available plant was applied as heat source for tapering. The temperature adjustment was controlled by variation of the vertical distance between the fiber and the flame. Additionally, two precisely controlled motor stages were installed to allow accurate alignment and tapering of the IF. Due to the tapering process, the NA of the input pump light approximately increases by a factor of the taper ratio (TR) [15], which is defined as the ratio of the original fiber diameter to the diameter of the taper waist. After tapering, the IF is twisted once around the 3C-fiber, which ensures that the converging taper portion remains in contact during lateral fusing. The overlap area between the 3C-fiber and the IF is defined as the fusion zone. Due to the tapering process the NA of the guided pump light is increased. The pump light propagating at higher NAs couples into the 3C-fiber in the fusion zone. The final lateral fusion process along the fusion zone was carried out at temperatures, which allow sufficient softening of the tapered IFs and only slight softening of the 3C-fiber. It results

TABLE I
Overview of the Fiber Parameters

	Diameter [µm]	Numerical aperture
3C core	34	0.065
3C sidecore	8-10	0.09
3C cladding	250	0.48
PF core	106.5	0.22
PF cladding	125	
IF cladding	125	0.46

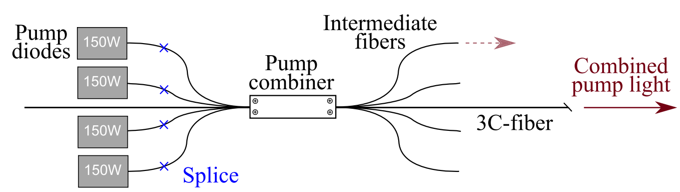

Fig. 2. 3C-fiber (34/250DC-3 C) combiner with up to four fiber coupled pump diodes (150 W each at 976 nm).

in a weakly fused component without any thermally induced damage of the core and the sidecore(s) of the 3C-fiber. Compared to the manufacturing process of combiners with typical standard fibers, the fusion process was temporally extended to increase the coupling efficiency of the final 3C-combiner. Pump light that does not couple into the 3C-fiber remains in the IF (transmitted pump light, see. Fig. 1) or emerges from the fiber as power leakage into the housing of the combiner.

For the manufacturing process of the signal and pump combiner a variety of fiber types are used. An overview of the used fiber parameters is presented in Table I.

III. Characterization of a Multi Pump Port 3C-Fiber Combiner

In high power all-fiber laser and amplifier systems, it is typically required to provide multiple pump ports due to the limited output power of commercially available fiber coupled pump diodes. Therefore, we developed a 3C-fiber combiner with up to four pump ports. The setup of each component is identical to the description in Section II and is shown in Fig. 2. The combiner is directly integrated in a passive 3C-fiber (34/250DC-3 C, *nLight*) and four fiber coupled pump diodes each with an output power of 150 W at 976 nm are spliced with a matched core diameter of 106.5 μm on the input pump fibers of the pump combiner. The combined pump light in the 3C-fiber and the residual light in the

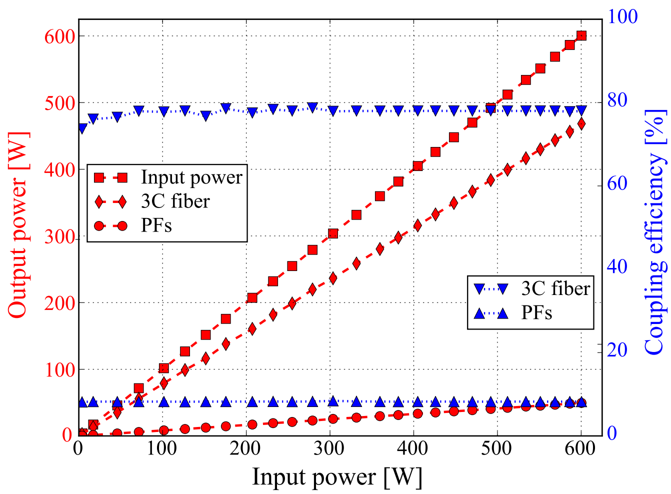

Fig. 3. Experimental output power results (red) of the combined pump power for a 4+1x1 high-power fiber combiner integrated in a 3C-fiber. The corresponding coupling efficiency of total diode power to the 3C-fiber is shown in blue in percent.

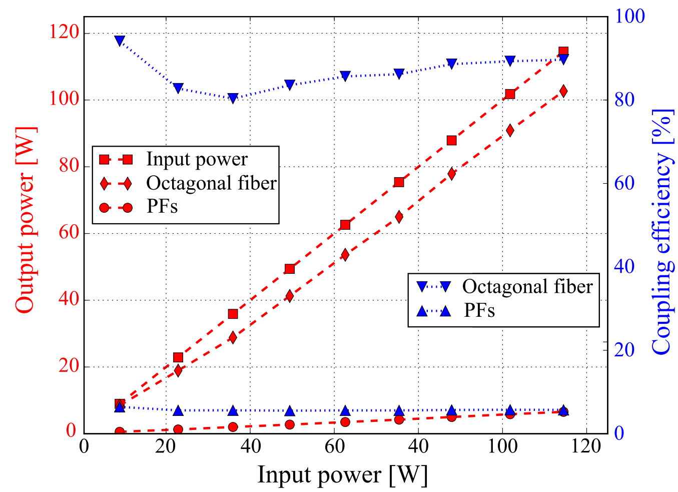

Fig. 4. Experimental output power results (red) of the combined pump power for a 2+1x1 high-power fiber combiner integrated in a standard fiber with a octagonal structure. The corresponding coupling efficiency of total diode power to the signal fiber is shown in blue in percent.

IFs are afterwards detected with a power head. The experimental results are presented in Fig. 3 and show the combined pump power (red diamonds) and the residual transmitted pump light (red circles) with respect to the total diode power (red squares). At the maximum total diode power of 600 W a corresponding combined pump power of 465 W was measured, which corresponds to a coupling efficiency of 78% (blue down-triangle). Previously developed side-pumped combiners with standard commercially available large mode area (LMA) fibers achieved a coupling efficiency of up to 93% in theoretical simulations and 92% in experimental components [15]. Possible reasons for the lower achieved efficiency are explained in the following section IV. The amount of the pump light in the IFs (blue up-triangle) was 8.4% compared to the total diode power. Accordingly, the residual pump light was lost in ways as described in Section II, which led to elevated temperatures of the combiner housing ($\sim 50^{\circ}$C). The insertion loss for backwards travelling pump light into one of the pump input fibers was measured to be $\sim$10%. I.e., in a case of a bidirectional pumping system even if a low pump absorption of only 10 dB is assumed, only 1% would couple back into the laser diodes. Thus, such a device is well suited for a bidirectional pumping system.

IV. Detailed Investigations of a Multi Pump Port 3C-Fiber Combiner

Possible reasons for the reduction of the coupling efficiency of the 3C-fiber signal and pump combiner compared to standard LMA components is considered in more detail in the following.

To achieve an improved pump absorption the 3C-fiber has an octagonal cladding structure. In the drawing process of the 3C-fiber, the fiber is twisted to achieve the helical design with rotating sidecores. Thus, the cladding surface shows a slight wavy structure along the fiber. To investigate the influence of the octagonal structure and the additional pattern of the surface on the coupling efficiency, an additional combiner integrated in

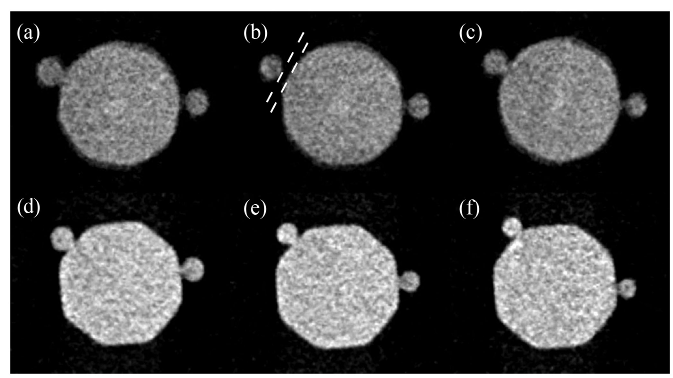

Fig. 5. Cross-section images of a two port 3C-fiber pump combiner in (a) – (c) and of a pump combiner based on a fiber with octagonal cladding structure in (d)–(f) at different positions in the combiner. The two PFs are at all time in contact with the octagonal fiber, whereas the IF is not permanently attached on the 3C-fiber.

a fiber with an octagonal cladding structure (Passive-250DC-O, *LIEKKI*) was manufactured under the same conditions. The measured performance of this 2+1x1 fiber combiner with octagonal cladding structure is presented in Fig. 4. At an input pump power of 114 W a combined output power of 102.7 W was measured, which corresponds to a coupling efficiency of 90.1%. Thus, it appears that the rotation of the octagonally shaped cladding (or a combination of the resulting longitudinal pattern and the octagonal cladding structure) prevents similar coupling efficiencies of the 3C-fiber pump combiner compared to a standard fiber combiner. The technique of an X-ray computer tomography enables a closer examination from the detailed construction of each combiner. Therefore, a two port 3C-fiber pump combiner was manufactured using the same procedure.

The images in Fig. 5 reveal the direct composition of the component and the overlap of the IFs and the signal fiber. In Fig. 5(a) – (c) a pump combiner is shown integrated in a 3C-fiber and in (d) – (f) integrated in a standard fiber with an octagonal cladding structure. In the pump combiner with the octagonally

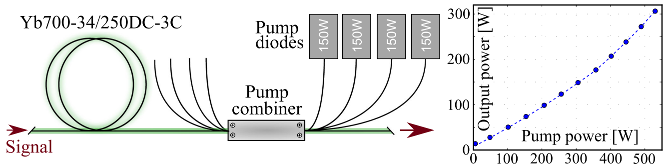

Fig. 6. Experimental setup of an all-fiber amplifier based on a pump combiner directly integrated in an Yb-doped 3C-fiber. Four fiber-coupled pump diodes each with 150 W at 976 nm amplifies an input signal to an output power level of more than 300 W.

shaped fiber, the IFs are always attached to the signal fiber. This enables a successful coupling of the pump light into the signal fiber and an efficiency of 90.1% (see Fig. 4).

In the case of the 3C-fiber, there is not always an overlap with the IFs. Especially, the image in Fig. 5 (b) shows a significant gap between the 3C-fiber and the IF. These gaps result in an inefficient coupling of the pump light to the signal fiber and an increase of internal losses. These investigations lead to the conclusion that the modification of this pattern towards a flat surface is a promising task for further investigations and is taken into account for further improvements of the 3C-fiber combiner.

V. 3C-Fiber Combiner in a Side-Pumped Amplifier

The SPC was also tested in a single-frequency all-fiber amplifier based on an Yb-doped 3C-fiber with a core and cladding diameter of $34\,\mu$m and $250\,\mu$m, respectively. Previous investigations of the general performance of 3C-fibers in amplifier architectures were demonstrated at a high-output power level with a high fundamental mode content in a co-pumped all-fiber system [11]. Here, for the first time, we designed a counter- and side-pumped all-fiber amplifier based on 3C-fibers.

The setup is presented in Fig. 6. The pump combiner is integrated in an Yb-doped 3C-fiber (Yb700-34/250DC-3 C). Four fiber-coupled pump diodes deliver the required pump power with an output power of 150 W at 976 nm. The presented design allows for a stable and robust amplifier and ensures a high-output power of more than 300 W with no onset of SBS at an excellent fundamental mode content of 93% measured with a scanning ring-cavity [5]. This single-frequency amplifier emphasizes the high potential of highly-integrated signal and pump combiner in 3C-fibers, which can be implemented in almost any fiber laser or amplifier. The details and characterisation of this single-frequency amplifier system will be published elsewhere.

VI. Conclusion

An advanced optical design of a highly-integrated signal and pump combiner implemented for the first time in a chirally-coupled-core fiber has been presented in this paper. Using the side-pumping technology, an uninterrupted core of the 3C-fiber ensures an excellent beam quality due to the maintained design properties of the specialty fiber. The realized optical fiber component avoids an additional fusion splice in conjunction with signal mode matching as it is needed for fused tapered fiber bundles. With four fiber coupled pump diodes, a maximum power handling of 600 W was achieved with a coupling efficiency of 78% and enabled a high power signal transmission in forward and backward direction. However, the special design of the 3C-fiber also allows opportunities for further improvements of the coupling efficiency. The presented design of a 3C-fiber combiner enabled a stable and robust all-fiber amplifier. The optical properties of the 3C-fiber ensured a high fundamental mode content over 90% at a high output power of more than 300 W with no onset of SBS or other parasitic effects.

In conclusion, this 3C-fiber combiner offers the potential to realize compact and robust fiber lasers and amplifiers in combination with the advantages of specialty fibers to overcome current limitations due to nonlinear effects.

VII. Acknowledgment

The authors would like to thank Prof. Willke of the Albert-Einstein-Institut Hannover for the successful and on-going cooperation in the field of single-frequency laser systems for GWDs.

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